University of Victoria

ELEC 340

Applied Electromagnetics and Photonics

Lab 3 - Normal Incidence and Reflection Transmission

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A01 - B03

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1 Objective

Upon completion of the lab you should be able to:

1. Have a good understanding of the electromagnetic theory that governs the reflection and transmission of uniform plane waves at normal incidence.

2. Use computer software and smith charts to solve reflection and transmission problems.

3. Design electromagnetic impedance transformers.

2 Introduction

This lab uses a parallel plate wave guide filled with two different dielectrics to investigate reflection and transmission. When a uniform plane waves hits the boundary between two different dielectrics part of it is transmitted into the second medium and part of it is reflected back. The reflected wave interferes with the incident wave and creates a standing wave. This process is shown in Fig. 1.

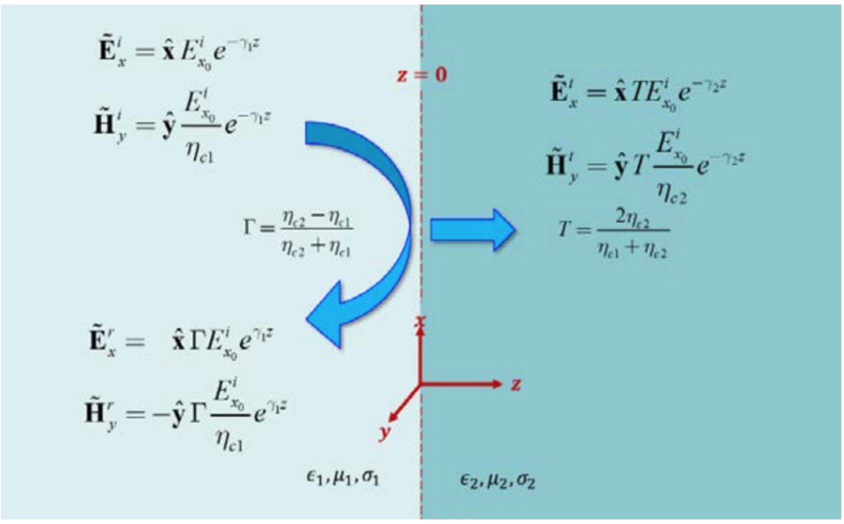


Figure 1: Reflection and transmission of a uniform plane wave at a normal material boundary

The reflection and transmission coefficientcs, Γ and T, are given by:

$$\Gamma = \frac{E_{x0}^r}{E_{x0}^i} \qquad\qquad T = \frac{E_{x0}^t}{E_{x0}^i} \tag{1}$$

The total electric and magnetic fields in the first material will be the sums of their incident and reflected components. If the phase of the reflected wave is not $\pm 90°$, the total field will have both a traveling and a standing component. The magnitude of the total wave will be bounded by $E^i_{x0}\,(1 \pm |\Gamma|)$.

For multiple boundaries, this analysis can be applied recursively starting at the medium furthest from the incident wave and working towards it.

3 Procedure

A waveguide was constructed in MEFiSTo and filled with two dielectric media, as shown in Fig. 2.

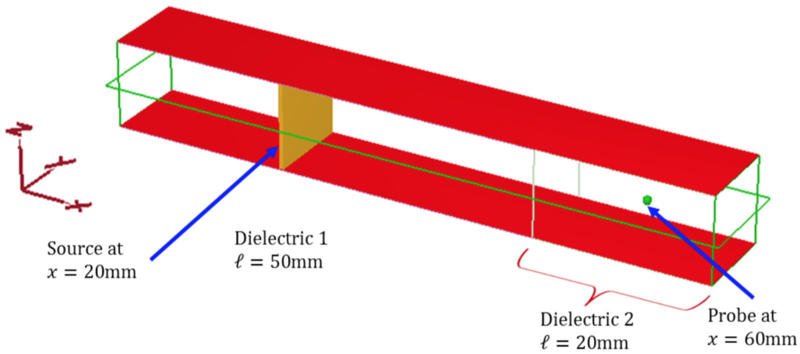


Figure 2: Parallel plate waveguide

Initially, we made both dielectrics identical and changed the right end to a perfect electrical boundary. The source generated a 10 GHz plane wave through the structure. By observing the wave envelope in the structure we were able to determine the standing wave amplitudes, $E_{max}$and E_{min}, and positions of l_{max} and l_{min}. The type of right boundary (absorbing, electric, magnetic) was changed, as well as the dielectric properties ϵ_r and σ. See Section 4 for the effect of these variations of the wave patterns.

A third material was added to study the use of dielectrics as impedance transformers. The structure is shown in Fig. 3

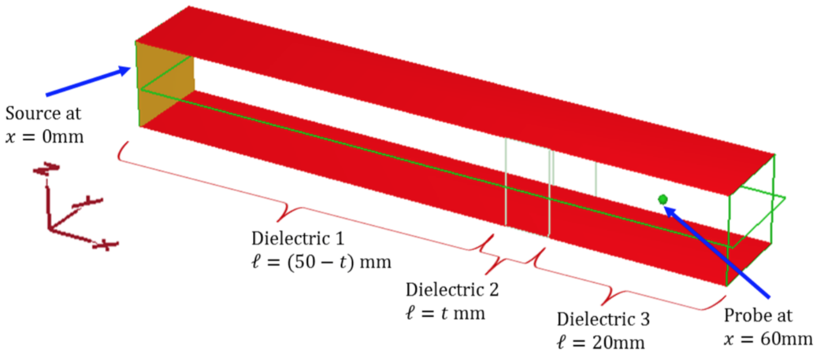


Figure 3: Waveguide with three dielectric regions

By choosing the length of the second dielectric region as $\lambda_2/4$ and $\epsilon_2 = \sqrt{\epsilon_1 \epsilon_3}$, we were able to create several impedance transformers by varying the length of the second medium and by using different pairs of input frequency and medium size.

4 Discussion

4.1 Traveling standing waves at normal incidence

Change the absorbing boundary in the second medium to a perfect electric boundary.

Task 2a *Identify the standing and traveling wave in the structure.*

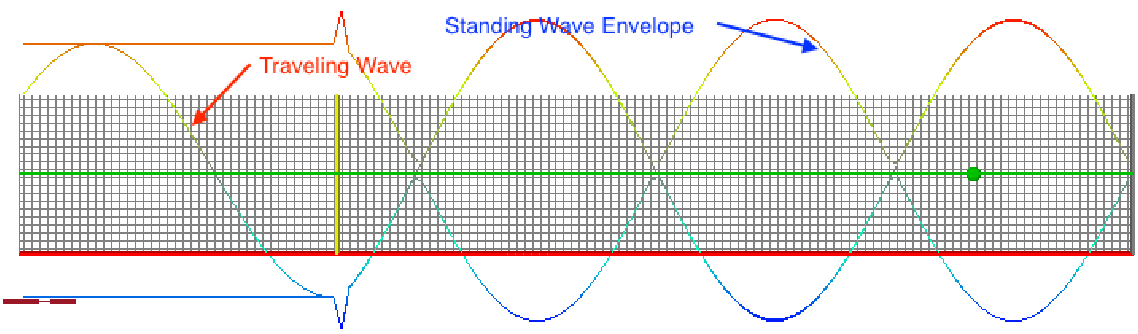
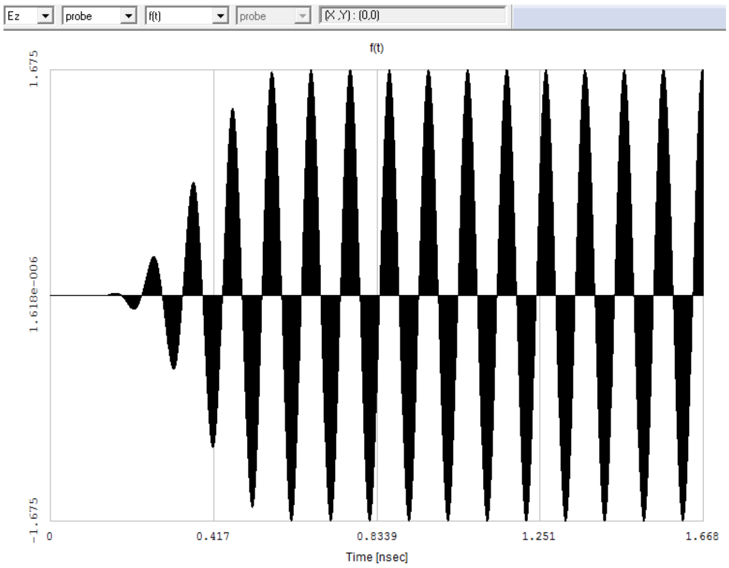


Figure 4: Standing wave pattern for waveguide with electric boundary at right end

Task 2b *What is the amplitude of the wave at the probe? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*



The amplitude of the standing wave is $1.675\,\mathrm{V\,m^{-1}}$ because the probe is not located at a standing wave antinode: odd integer multiples of l_{max}.

Task 2c *What is the amplitude of the wave to the left of the source region? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*

Fig. 4 shows that the wave has an amplitude of $2\,\mathrm{V\,m^{-1}}$. This is because the reflected wave is in phase with the source wave at the wave origin and constructive interference occurs.

Task 2d *What are:* $E_{max}, E_{min}, l_{max}, l_{min}, |\Gamma|, \phi_\Gamma$*? What are possible sources of error between the simulation and expected values?*

Parameter	Expected	Actual
E_{max}	$2\,\mathrm{V\,m^{-1}}$	$1.969\,\mathrm{V\,m^{-1}}$
E_{min}	$0\,\mathrm{V\,m^{-1}}$	$0.3478\,\mathrm{V\,m^{-1}}$
l_{max}	$62.5\,\mathrm{mm}$	$< 62.5\mathrm{mm}$
l_{min}	$55\,\mathrm{mm}$	$< 55\mathrm{mm}$
$\lvert\Gamma\rvert$	⅓	⅓
ϕ_Γ	$-\pi$ rad	$-\pi$ rad

The values of E differ from the expected values because the probes for those measurements were placed at the positions of l_{max} and l_{min} as determined by calculating the wavelength for $c_0 = 3.0 \times 10^8\,\mathrm{m\,s^{-1}}$.

Task 5a *Set* $\epsilon_{r2} = 4$, $\sigma_2 = 1\,\mathrm{S\,m^{-1}}$ *and repeat Task 2 with an absorbing right boundary.*

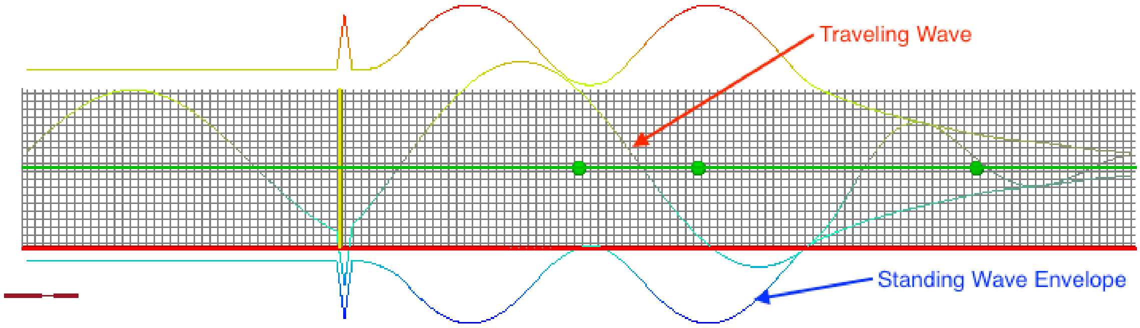
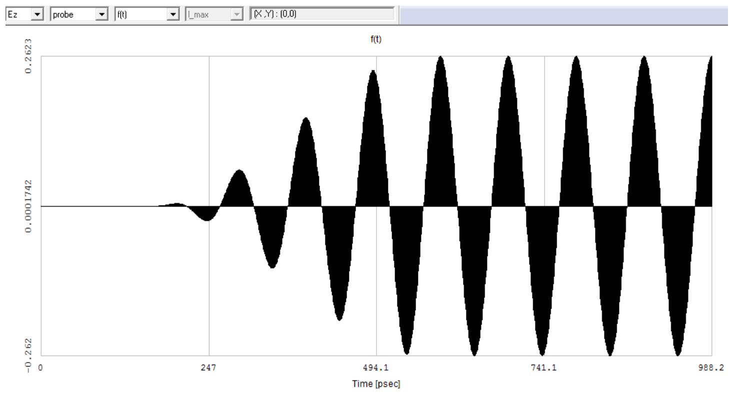


Figure 5: $\epsilon_{r2} = 4$, $\sigma_2 = 1\,\mathrm{S\,m^{-1}}$, absorbing right boundary

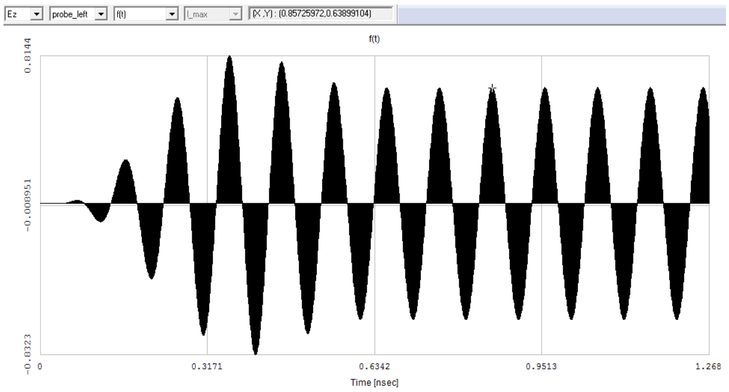
A standing wave envelope is produced between the source and dielectric boundary. As the wave enters the second medium it is attenuated.

Task 5b *What is the amplitude of the wave at the probe? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*



The amplitude is $0.263\,\mathrm{V\,m^{-1}}$. As noted in 2b, the source is not placed at an antinode. Also, the wave attenuates as it enters the second medium because $\sigma_2 \neq 0$.

Task 5c *What is the amplitude of the wave to the left of the source region? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*



The amplitude is $0.639\,\mathrm{V\,m^{-1}}$, which is close to the value of E_{min}. This is because destructive interference occurs when the wave reaches the source origin.

Task 5d *What are:* $E_{max}, E_{min}, l_{max}, l_{min}, |\Gamma|, \phi_\Gamma$*? What are possible sources of error between the simulation and expected values?*

Parameter	Expected	Actual
E_{max}	$1.33\,\mathrm{V\,m^{-1}}$	$1.365\,\mathrm{V\,m^{-1}}$
E_{min}	$0.67\,\mathrm{V\,m^{-1}}$	$0.6414\,\mathrm{V\,m^{-1}}$
l_{max}	$42.5\,\mathrm{mm}$	> 42.5mm
l_{min}	$50\,\mathrm{mm}$	> 50mm
$\lvert\Gamma\rvert$	⅓	0.36
ϕ_Γ	$-\pi$ rad	$-\pi$ rad

Again, error comes from approximating c_0.

Task 6a *Set* $\epsilon_{r1} = 9$, $\sigma_1 = 0.5\,\mathrm{S\,m^{-1}}$ *and repeat Task 5.*

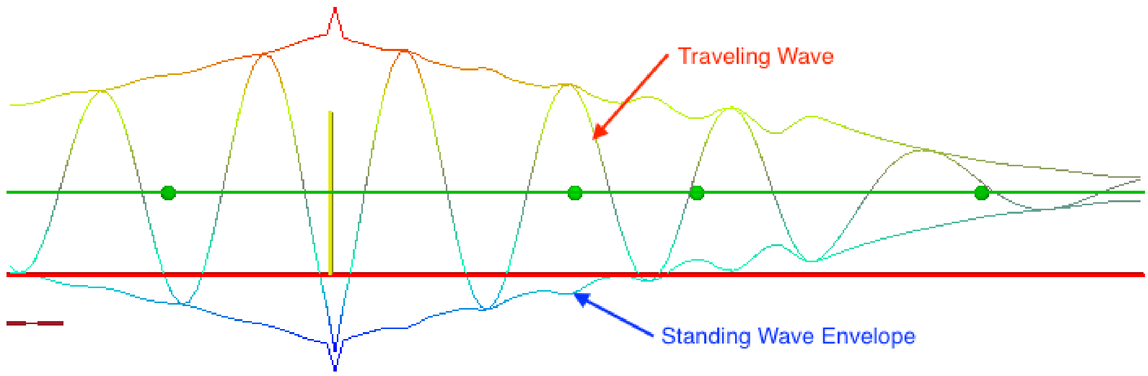
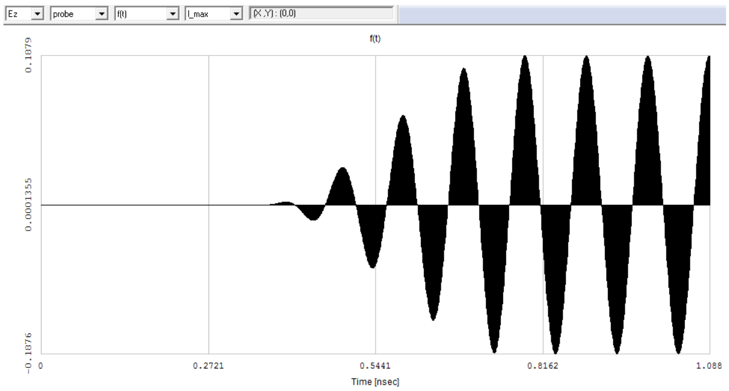


Figure 6: $\epsilon_{r1} = 9$, $\sigma_1 = 0.5\,\mathrm{S\,m^{-1}}$, $\epsilon_{r2} = 4$, $\sigma_2 = 1\,\mathrm{S\,m^{-1}}$

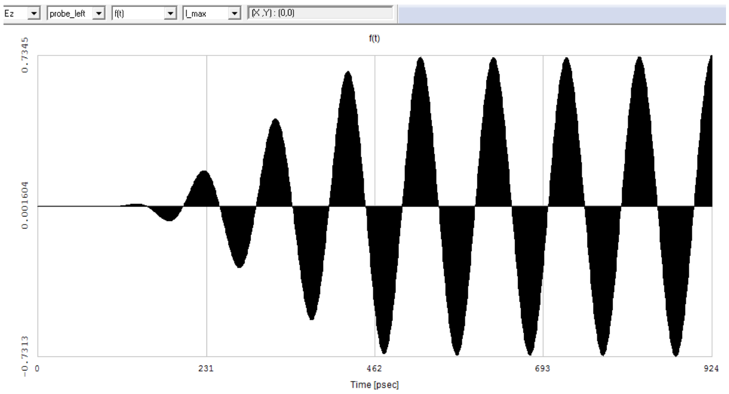
The wave attenuates in the first dielectric because $\sigma_1 \neq 0$.

Task 6b *What is the amplitude of the wave at the probe? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*



The amplitude is $0.1879\,\mathrm{V\,m^{-1}}$. It is smaller than in 5b because the wave attenuated in the first medium.

Task 6c *What is the amplitude of the wave to the left of the source region? Is it* $2\,\mathrm{V\,m^{-1}}$*? Why?*



The amplitude is $0.7345\,\mathrm{V\,m^{-1}}$ at the location of the leftmost probe in Fig. 6. At the location just to the left of the source it has an amplitude of $1\,\mathrm{V\,m^{-1}}$. Since the reflected wave is $90°$ out of phase it does not receive constructive or destructive interference.

Task 6d *What are:* $E_{max}, E_{min}, l_{max}, l_{min}, |\Gamma|, \phi_\Gamma$*? What are possible sources of error between the simulation and expected values?*

Parameter	Expected	Actual
E_{max}	$0.749\,\mathrm{V\,m^{-1}}$	$0.6587\,\mathrm{V\,m^{-1}}$
E_{min}	$0.436\,\mathrm{V\,m^{-1}}$	$0.4573\,\mathrm{V\,m^{-1}}$
l_{max}	$42.5\,\mathrm{mm}$	$> 42.5\mathrm{mm}$
l_{min}	$50\,\mathrm{mm}$	$> 50\mathrm{mm}$
$\|\Gamma\|$	0.20	0.18
ϕ_Γ	0 rad	0 rad

Error is introduced in the calculation of $|\Gamma|$ because measurements of successive nodes and antinodes to find the SWR does not account for the effect of attenuation. This causes SWR to be larger than expected, thus $|\Gamma|$ is smaller than expected. A similar error is introduced when calculating E_{max} and E_{min}.

Task 8 *Design an impedance transformer with minimum thickness so that a 7.5 GHz wave can pass through without reflection.*

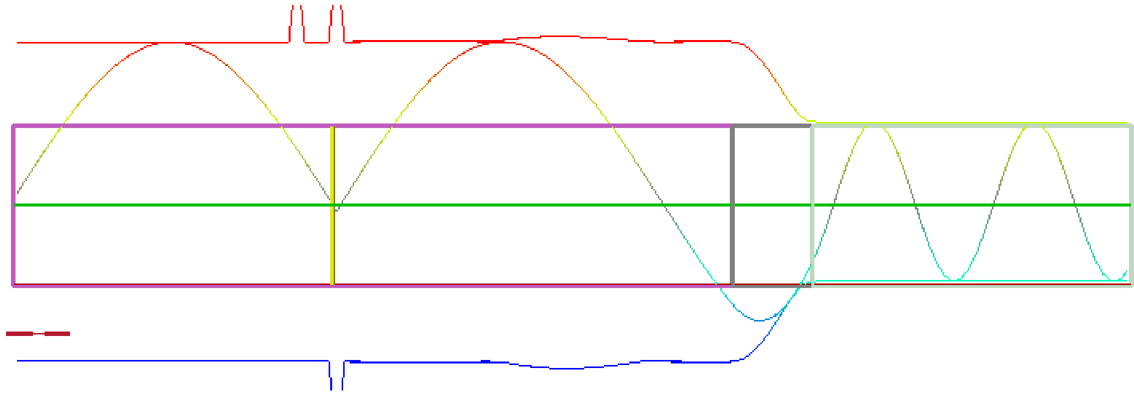


Figure 7: Impedance tranformer with $\epsilon_{r2} = 4$ and $d = 5\,\mathrm{mm}$

For this configuration, $\epsilon_{r1} = 1$ and $\epsilon_{r3} = 16$. Thus

$$\epsilon_{r2} = \sqrt{\epsilon_{r1}\epsilon_{r3}} = 4$$

and

$$d = \frac{\lambda_2}{4} = \frac{c_0}{4\sqrt{\epsilon_{r2}}f} \approx 5\,\mathrm{mm}.$$

Task 10 *Modify the impedance transformer from Task 8 to the third minimum thickness.*

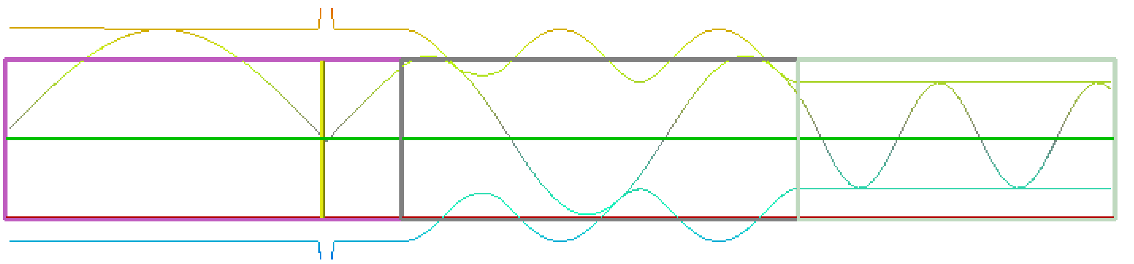
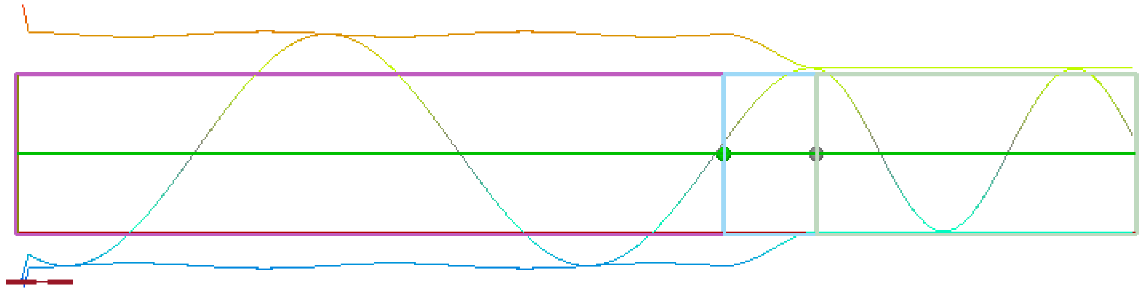


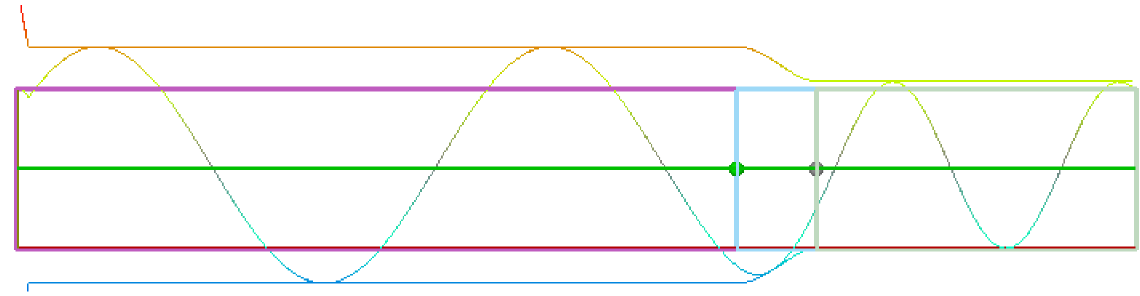
Figure 8: Impedance tranformer with $\epsilon_{r2} = 4$ and $d = 25\,\mathrm{mm}$

Successive impedance transformers can be created by adding integer multiples of $\lambda_2/2$.

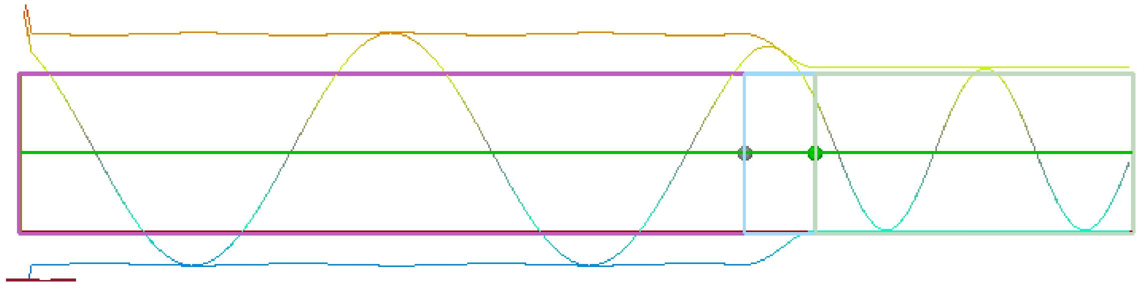
Task 11 & 12 *Set $\epsilon_{r1} = 2$ and $\epsilon_{r3} = 8$ and perform simulations for 6.5, 7.5, 8.5 GHz.*



(a) $f = 6.5\,\text{GHz}$, $d = 5.8\,\text{mm}$



(b) $f = 7.5\,\text{GHz}$, $d = 5\,\text{mm}$



(c) $f = 8.5\,\text{GHz}$, $d = 4.41\,\text{mm}$

Figure 9: Impedance transformers for $\epsilon_{r1} = 2$ and $\epsilon_{r3} = 8$

As for Task 8, $\epsilon_{r2} = 4$ and d is a quarter wavelength in material 2.

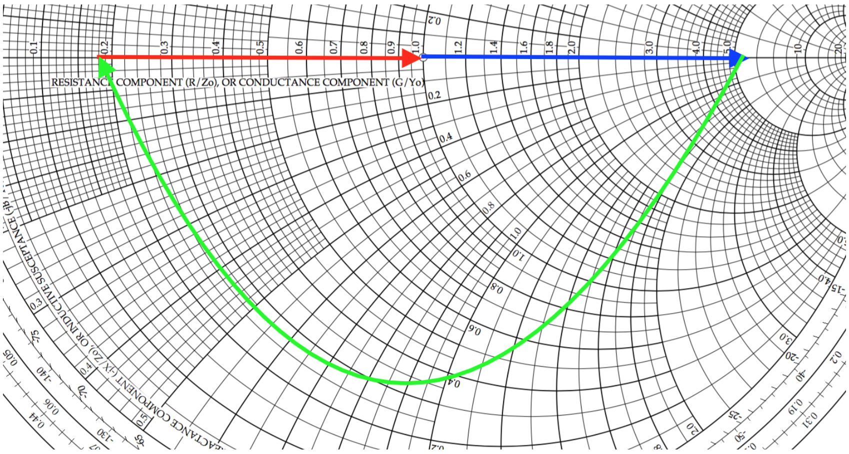
Parameter	6.5 GHz	7.5 GHz	8.5 GHz
E_{max}	$1.001\,\text{V}\,\text{m}^{-1}$	$0.9979\,\text{V}\,\text{m}^{-1}$	$0.9988\,\text{V}\,\text{m}^{-1}$
E_{min}	$0.7055\,\text{V}\,\text{m}^{-1}$	$0.7062\,\text{V}\,\text{m}^{-1}$	$0.7061\,\text{V}\,\text{m}^{-1}$
l_{max}	$44.2\,\text{mm}$	$45\,\text{mm}$	$45.59\,\text{mm}$
l_{min}	$50\,\text{mm}$	$50\,\text{mm}$	$50\,\text{mm}$
$\lvert\Gamma\rvert$	0.176	0.176	0.176
ϕ_Γ	$-\pi$ rad	$-\pi$ rad	$-\pi$ rad

Sample calculations

$$|\Gamma| = \frac{SWR - 1}{SWR + 1} = \frac{\frac{1}{0.7} - 1}{\frac{1}{0.7} + 1} = \frac{0.4286}{2.4286} = 0.176$$

$$\phi_\Gamma = -\pi - \frac{4\pi}{\lambda} z_{min} = -\pi - \frac{4\pi}{\lambda}(0) = -\pi$$

This transformation can be shown on a Smith chart:



The blue arrow shows the material 2 to 3 transition; the green arrow shows the wave moving through a quarter wavelength of material 2, and; the red arrow show the material 1 to 2 transition.

Since all three frequencies have the same values for $|\Gamma|$ and relative permittivities, the Smith charts are identical.

5 Conclusion

The simulations in the lab vividly showed the electromagnetic theory that governs plane wave transmissions and reflections in a material at normal incidence. It demonstrated how the waves behave in the first and second medium, especially the interactions of the incident wave and the reflected wave in the first medium.

The simulation software can be used to check the calculations to see if the simulation and the calculation match up. The reflection and transmission problems can be calculated using Smith charts.

Electromagnetic transformers can be designed using the material properties and using materials with specific permittivity and adjusting the length of material sections to allow a specific amount of transmission.