Design of TE20 to TE10 Rectangular Waveguide Mode Converters

ECE 6310 Spring 2024 Project

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Introduction and Motivation

Waveguides are useful for transmitting high power microwaves with low losses. They can support multiple modes of propagation simultaneously depending on the dimensions of the waveguide and the frequency of the microwaves. This project focuses on how to convert the energy of one propagation mode to another for a given waveguide and frequency. This paper explores the TE20 mode to TE10 mode conversion because they are less complex than higher level modes and the reference papers uses them. The purpose of this project was to learn more about waveguides and how to design them. This was also a good opportunity to learn how to use Ansys Electronics Desktop software better.

Waveguide Properties and Mode Conversion

A waveguide carries electromagnetic waves inside a conductive tube and for this project a rectangular waveguide can be used. Unlike coax cables which have two conductors and only support TEM waves. Wave guides only have one conductor which supports TE and TM waves. For simplicity the waveguides in this project will have a vacuum inside. The walls of the waveguide used a 5mm thick copper conductor.

As stated, earlier waveguides can have many modes of propagation depending on the dimensions of the waveguide and excitation frequency. The energy of these modes can be exchanged between one another depending on the waveguides shape. Mode conversion for TE20 to TE10 can be achieved by applying a bend in the H plane of the wave guide, see figure 1 x and z plane. The paper discussed three methods of mode conversion each with different use cases. The three mode converter designs are a single bend, a double bend with a length added in between, and a triple bend which allows for the waveguide to stay in the same plane and direction that it started in.

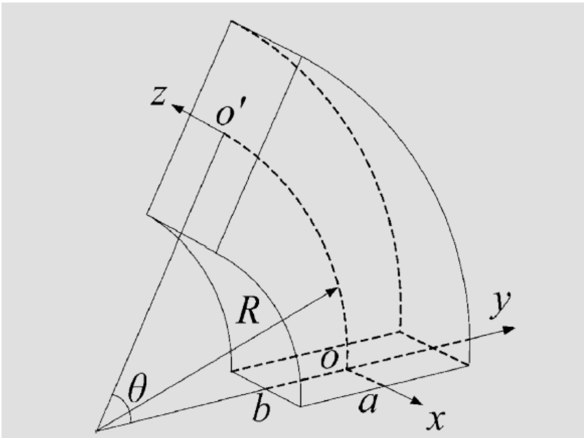

Figure 1 Curvilinear coordinate system use by the reference paper.

Waveguide Design Procedure

The approach of this project was to first create the waveguide geometry in Ansys electronics desktop. The geometry of the waveguide was designed to be highly adaptive by making its shape dependent on project variables. This means that the shape of the waveguide can be changed one at a time or swept by a simulation optimizer. The geometry used would be the same as the reference paper. These designs were simulated to validate the results of the reference paper.

After the simulations validated the results from the reference paper. A new approach was taken to find valid solutions for the wave guides. This approach was to sweep the variables controlling the dimensions of the waveguide bends to find values that had a high conversion efficiency. Once promising parameters were found an optimization could be run to try and maximize the mode conversion efficiency.

The next approach was to plot the formulas given by the reference paper and select valid dimensions that would give the highest conversion efficiency. These formulas were plotted using MATLAB. Once the optimal dimensions were found they could be entered into the Anys simulation and solved to see if the conversion efficiency was high as predicted.

Building the Waveguide Geometry in Ansys

I started by basing my waveguide design from the waveguide homework solution from earlier in the semester. This was just a simple straight rectangular waveguide with a wall thickness of 5mm. I appended new sections to the waveguide which were made up of stacks, bends, and straight sections. I implemented a bend in the geometry by linking it to a coordinate offset which is just a reference point relative to the true origin. After the sections were added they would be united into a single object.

Formulas were needed to calculate the x and y coordinates of the reference points which would guide where the bends would occur. The table below shows the formulas used for a triple bend mode converter, see figure 2 for a visual reference.

$x_2 = x_1$ -2*bend_radius*sin(180deg-bend_angle)
$y_2 = y_1$ -2*bend_radius*sin(180deg-bend_angle)
$x_3 = x_2$ -2*bend_radius*sin(bend_angle)
$y_3 = y_2$ -2*bend_radius*cos(180deg - bend_angle)

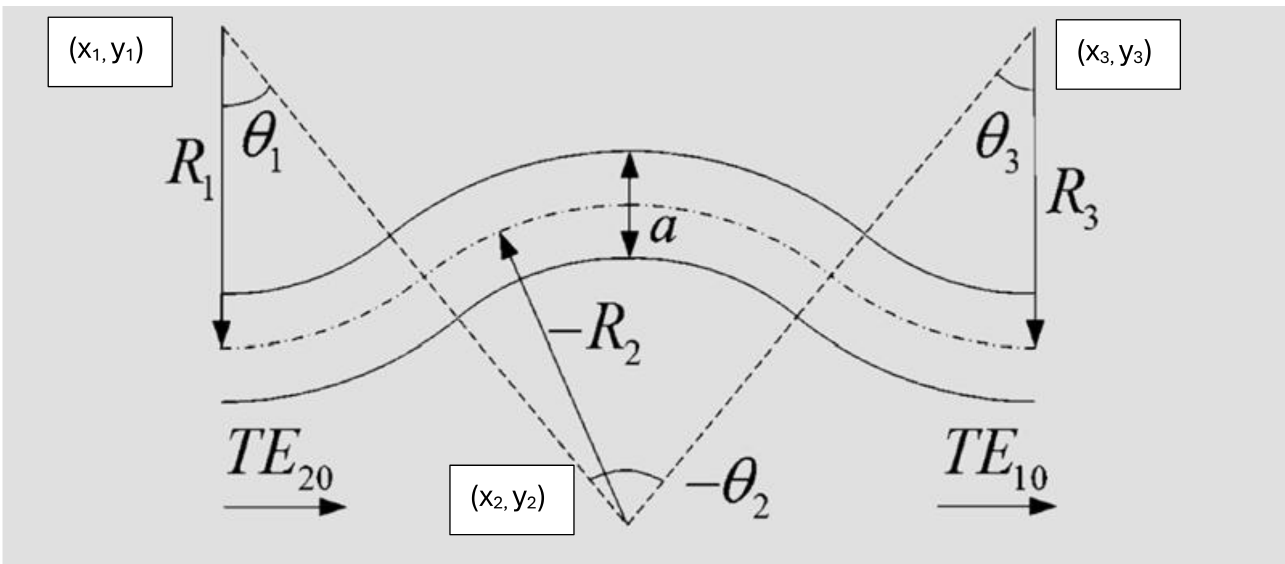

Figure 2 Geometry sketch of the tri-bend TE20-TE10 rectangular waveguide mode converter.

Validating Waveguide Solutions from Paper

After The adaptive geometry solution was working the next steps were to validate the solutions from the paper to ensure that the simulation was setup correctly.

Validation of Double Bend Mode Converter

The double bend with a straight middle section was chosen as the first simulation test, See figure 4. The simulation properties were configured as shown in the following list.

- TE10 to TE20 from Bottom to Top
- Bend Radius: 53.57 mm
- Bend Angle: 53.11 Degrees

- Middle Length: 134 mm
- Simulation Frequency: 8.5GHz
- Dimensions: 47.55x22.15 mm

The simulation did indeed show that a mode conversion was happening. Figure 3 shows the TE10 mode excited in the bottom of the waveguide and TE20 shows TE10 at the top or output of the waveguide.

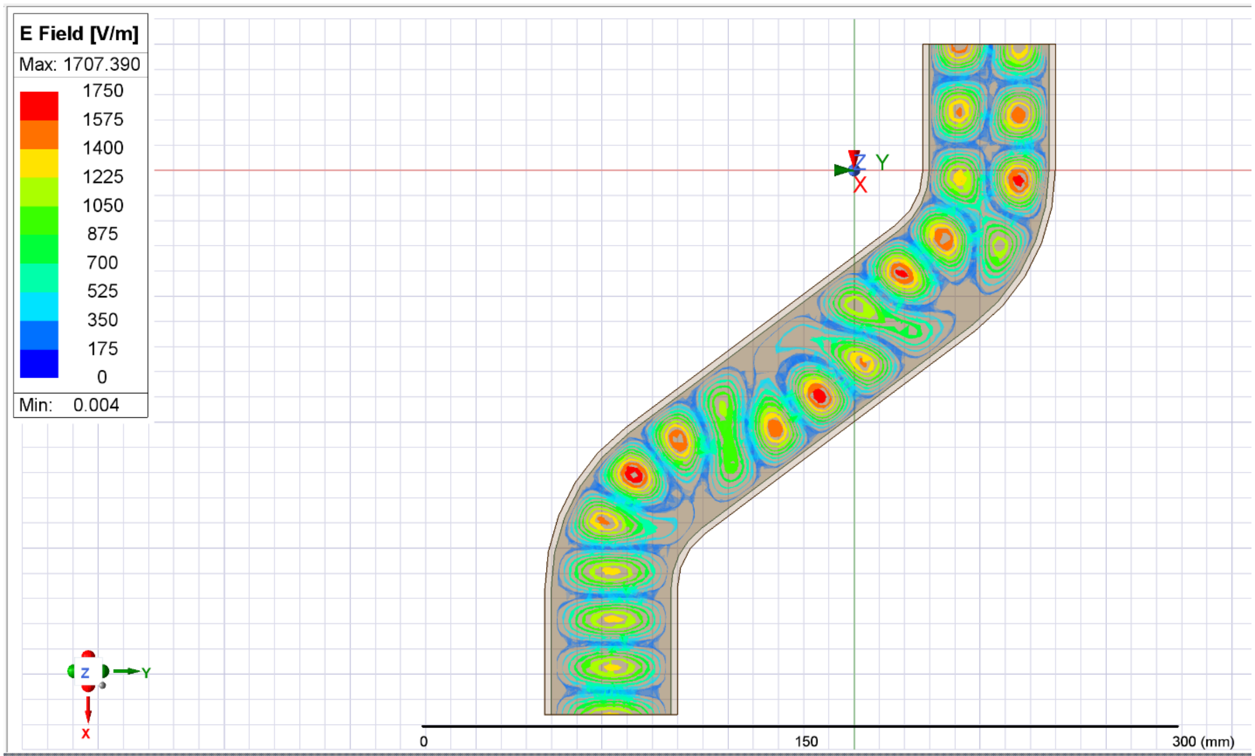

Figure 3 Double Bend waveguide with reference paper solution. This shows the E field magnitude looking down from the Z axis.

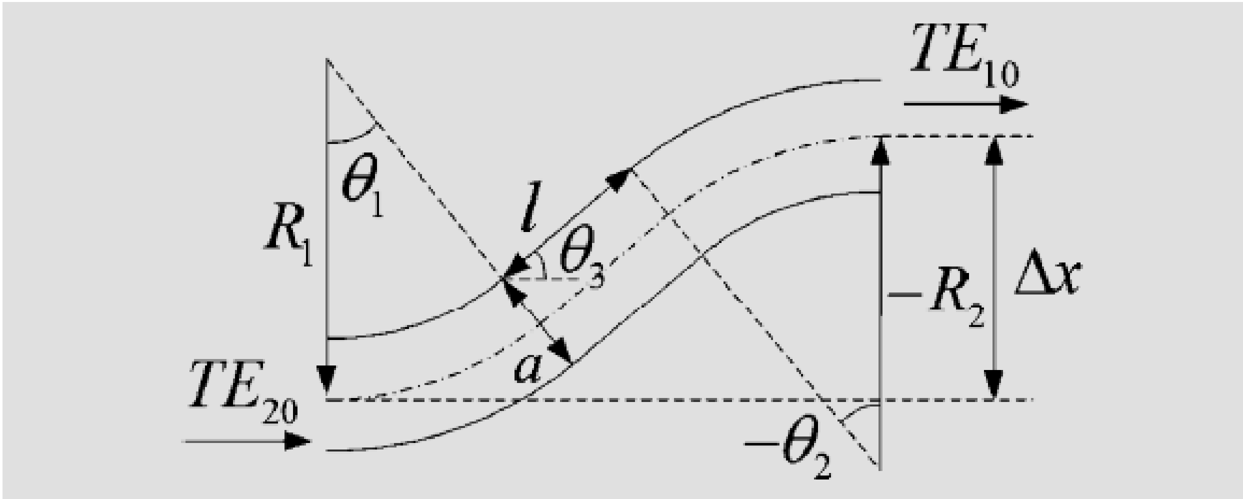

Figure 4 Geometry sketch of the combined dual-bend TE20-TE10 tectangular waveguide mode converter.

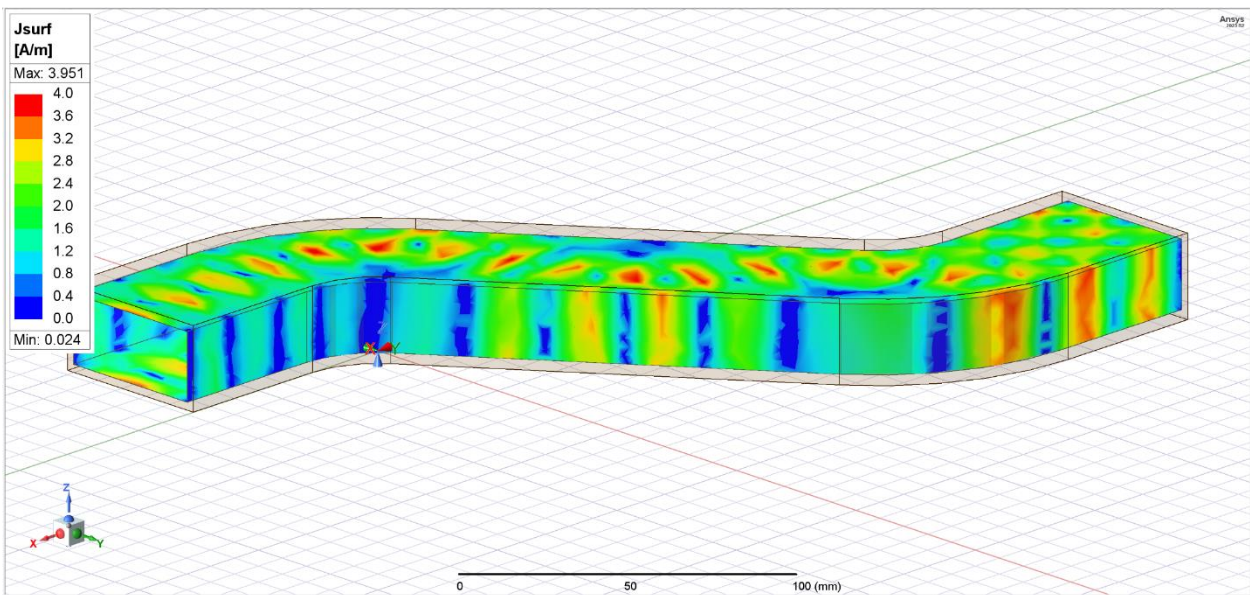

Figure 5 shows the surface current across the simulated waveguide in figure 3.

Validation of Triple Bend Mode Converter

As with the single bend mode converter a triple bend simulation was created and run to validate a triple bend solution from the reference paper. Figure 6 shows the TE10 mode entering the bottom of the waveguide and at the top of the waveguide a TE20 mode wave is at the exit. This shows a good conversion efficiency at the output.

- TE10 to TE20 from Bottom to Top
- Bend Radius: 76.08 mm
- Bend Angle: 28.02 Degrees
- Simulation Frequency: 8.5GHz

- Dimensions: 47.55x22.15 mm

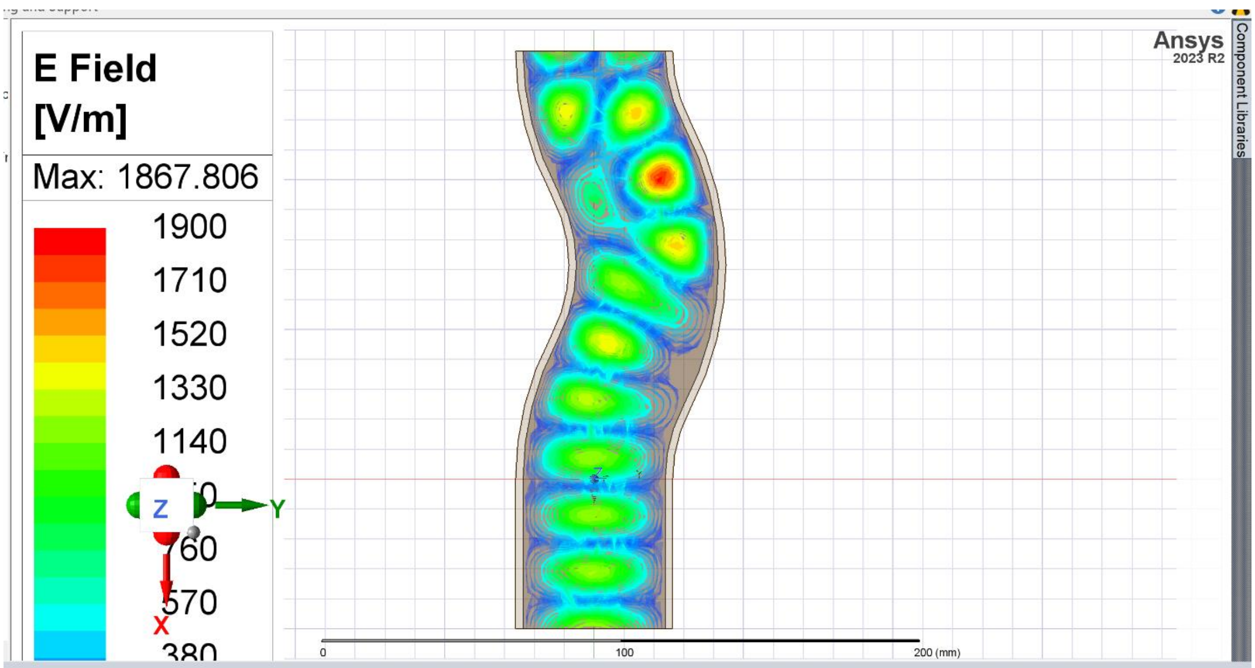

Figure 6 Triple bend mode converter. This shows the E field magnitude looking down from the Z axis.

The port fields for the triple bend simulation are shown in figure 7 which also comes with a reference from a textbook to what the modes should look like. The port fields match that of the textbook so it can confidently be said that the mode conversion in the simulation works and is of high efficiency. It also shows that the simulation matches the results from the reference paper.

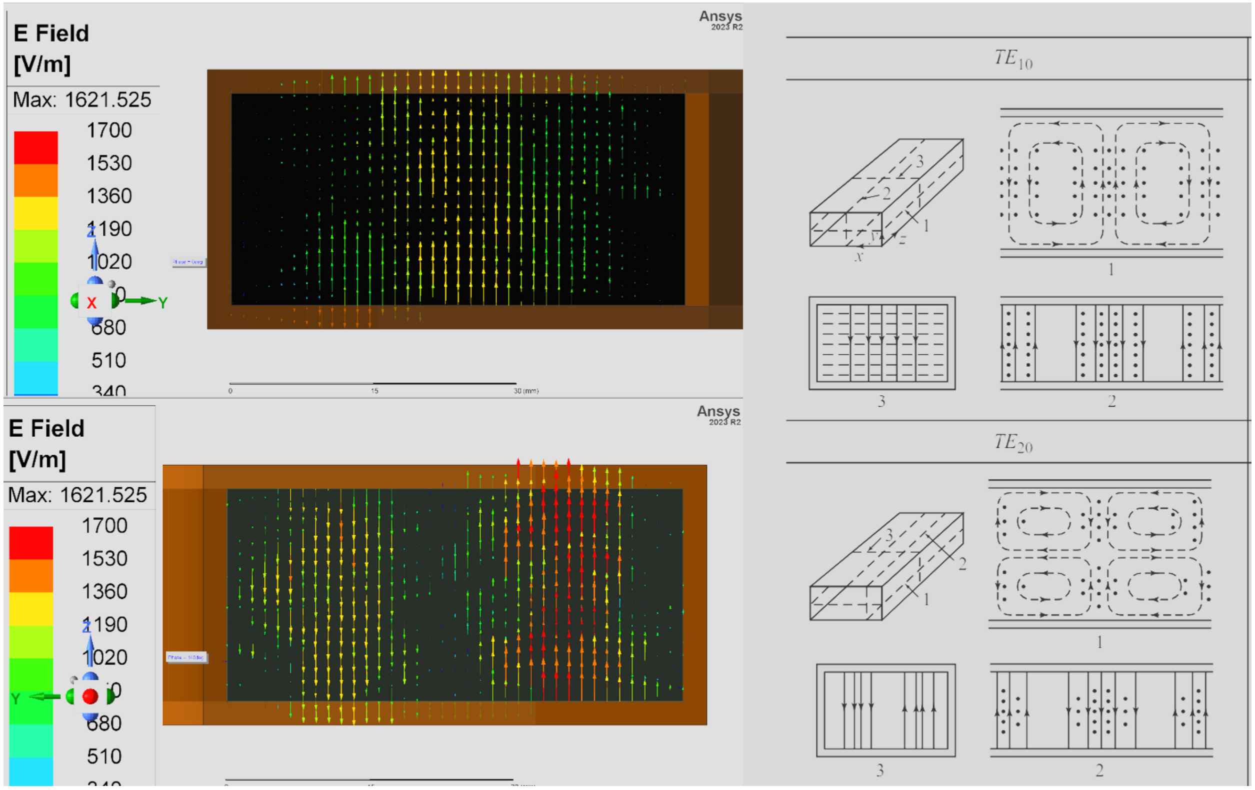

Figure 7 The port fields from the simulation shown figure 6. The diagram of the TE field configurations comes from Pozar Microwave Engineering Pg 118.

TE20 Propagation Experiment

A test was devised to see if the TE20 mode propagation was stable across a longer length of waveguide. To run this experiment the triple bend geometry was modified with a long length added to one side of the mode converting bends. The results of this experiment show that the TE20 mode is stable after a relatively long propagation distance. See figure 8 for a visual. The simulation configuration is as the following list shows.

- TE10 to TE20 from Right to Left
- Bend Radius: 76.08 mm
- Bend Angle: 28.02 Degrees
- Simulation Frequency: 8.5GHz
- Dimensions: 47.55x22.15 mm

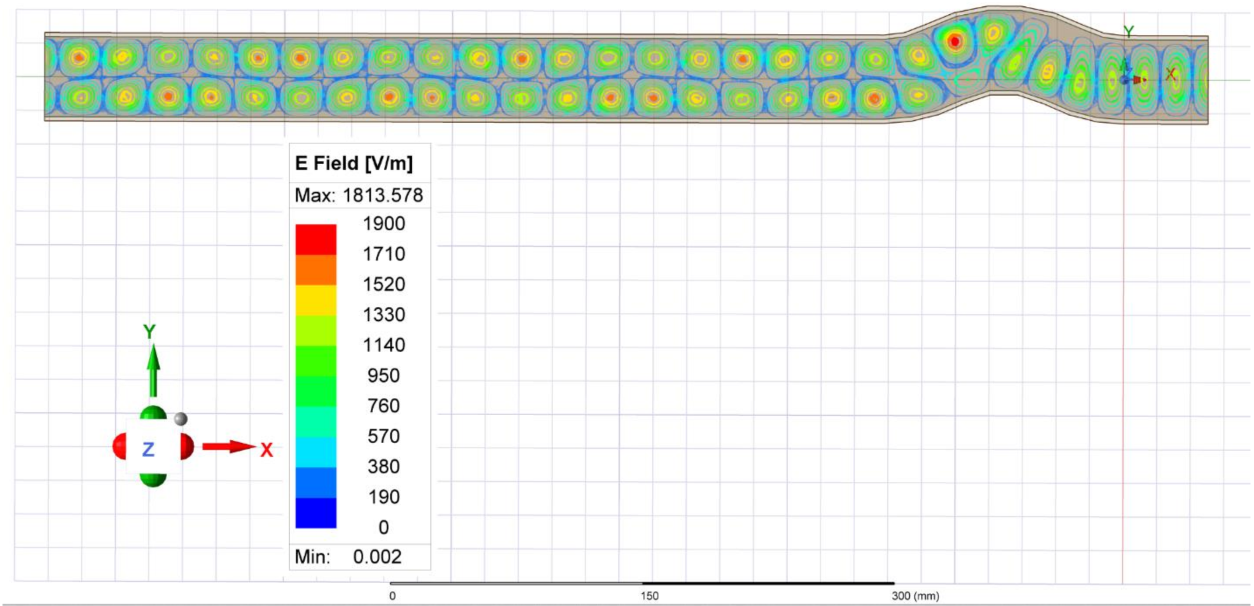

Figure 8 Long TE20 propagation.

Ansys Optimizer Testing

The waveguide geometry can be adjusted by using the variables Bend Radius, Bend Angle, and Middle Length (Two bend only). I wanted to see if I could use Ansys to find valid solutions to the TE20 to TE10 mode conversion without the use of the formulas given by the reference paper. There were two approaches used to have Ansys find valid solutions. The first approach was to run an Ansys optimizer with a goal to achieve and variables to change to get that goal. The second approach was to create a step parameterization of the variables and plot them all on top of each other. These approaches can use used together to speed up the simulation process.

Before running the optimizer, I wanted to see what results a random change to the waveguide variables would look like to see if it is easy or difficult to get TE20-TE10 mode conversion to happen.

Single Bend with Arbitrary Bend Radius

I made a single bend 90-degree simulation, see figure 9, with the following parameters. The bend radius was an arbitrary value that was chosen. The results of figure 9 show that the TE20-TE10 mode conversion efficiency is poor.

- Results - Little to no conversion
- TE10 to TE20 bottom to right
- Bend Radius: 66 mm

- Bend Angle: 90 Degrees
- Simulation Frequency: 8.5GHz
- Dimensions: 47.55x22.15 mm

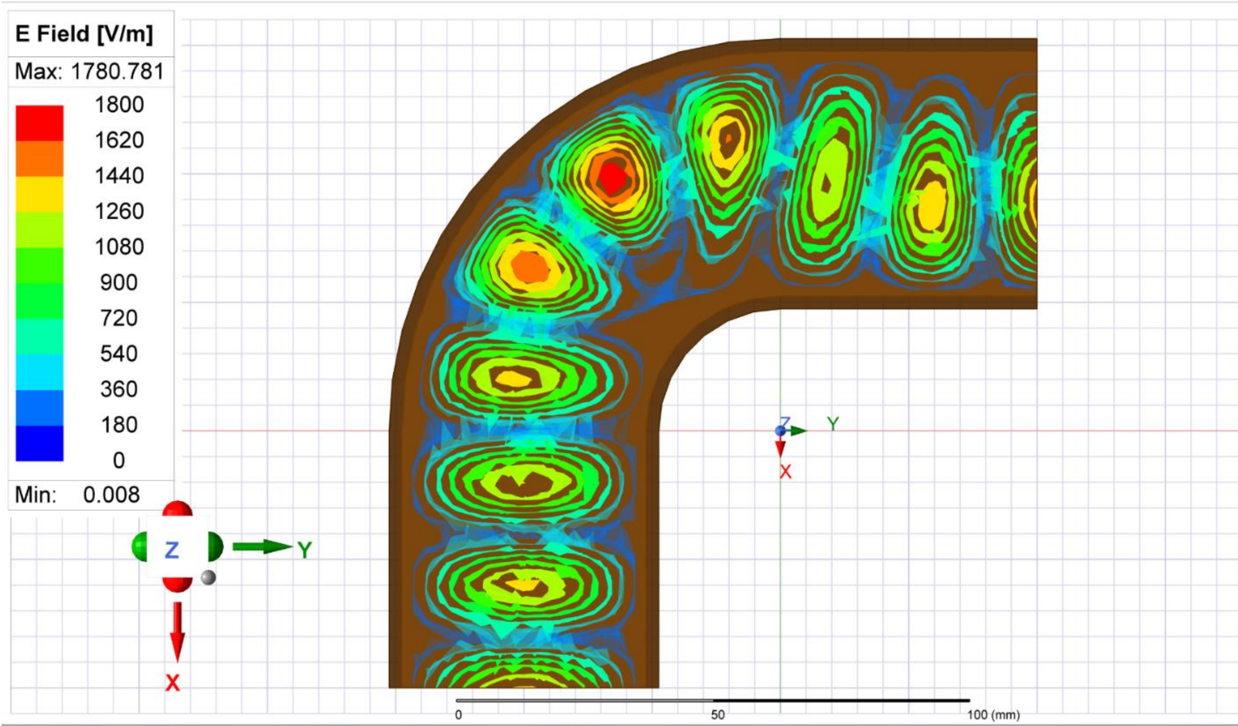

Figure 9 Single bend 90-degree bend angle.

Triple Bend with Arbitrary Bend Radius

I ran the simulation again with a triple bend configuration. The results in figure 10 show that the TE20-TE10 mode conversion efficiency is poor. I can conclude that getting a good efficiency is not easy.

- Results - Little to no conversion
- TE10 to TE20 bottom to top
- Bend Radius: 66 mm
- Bend Angle: 90 Degrees
- Simulation Frequency: 8.5GHz
- Dimensions: 47.55x22.15 mm

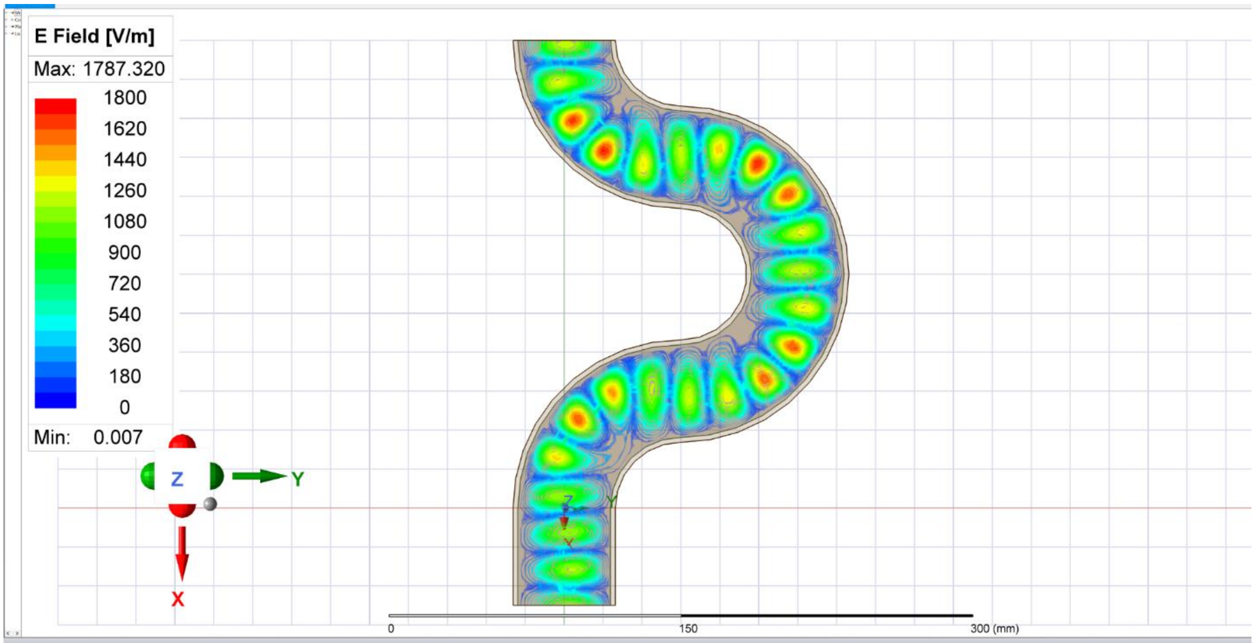

Figure 10 Triple bend simulation

Single Bend with a Parameterized Bend Radius

Another simulation was run with the bend radius as a variable. The plot shown in figure 11 shows multiple results but the pink line peaking near 8.5GHz is the best choice for the desired frequency of 8.5GHz. If a bend radius of 30mm is used the conversion efficiency will be near a maximum. This is a decent approach to getting a valid solution.

- TE10 to TE20
- Bend Radius: many
- Bend Angle: 90 Degrees
- Simulation Frequency: 8.5GHz
- Dimensions: 47.55x22.15 mm

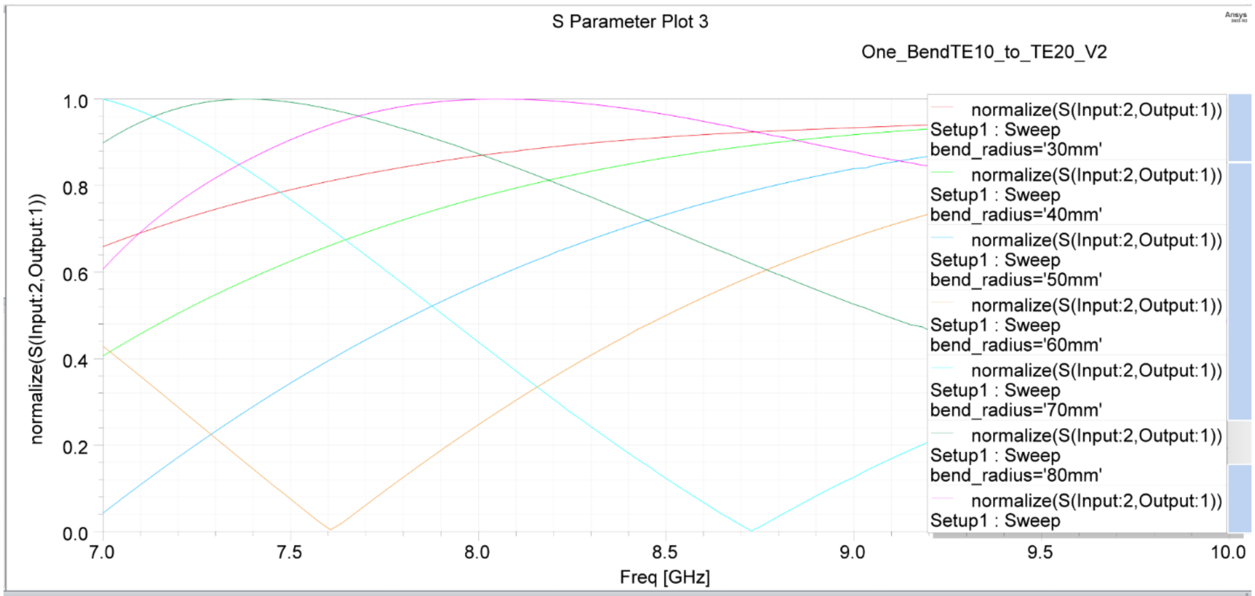

Figure 11 TE20-TE10 conversion efficiency with bend radius sweep.

Ansys Optimization Simulation of a Double Bend Mode Converter

Ansys was configured to try and find the maximum conversion efficiency of a double bend mode converter. The starting parameters we fixed so that it would be close to a maximum. Figure 12 shows how one of these optimizations was set up. Unfortunately, after many tries. I was unable to get good results with the optimizer. I may not have been setting it up correctly. If given more time this approach may be viable.

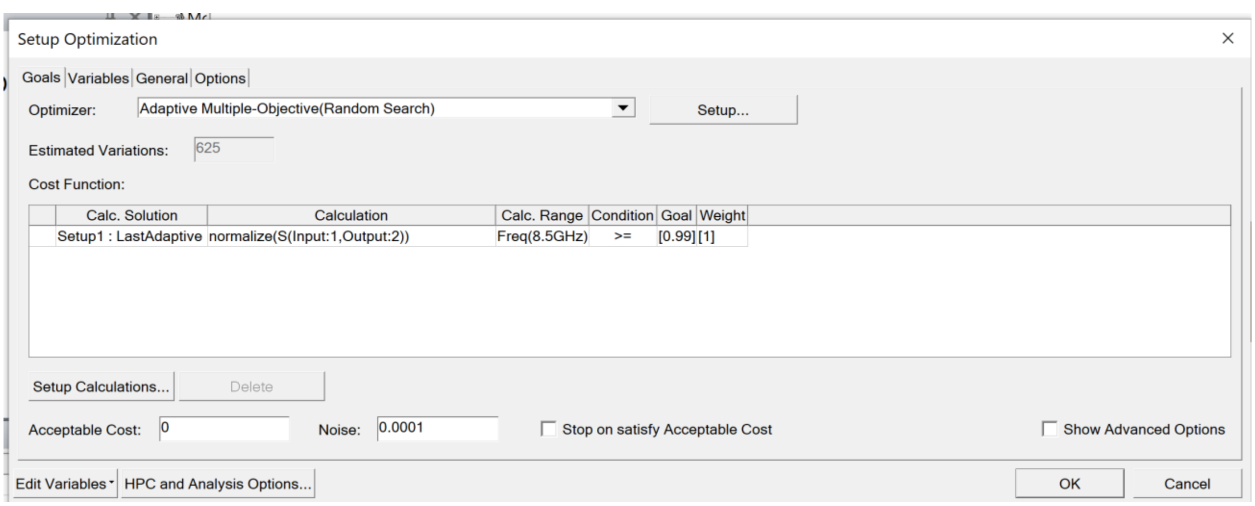

Figure 12 Optimization settings in Ansys.

Utilizing MATLAB and the Reference Paper’s Formulas to Find Valid Solutions.

This approach uses the formulas that are derived in the reference paper. These formulas are put into MATLAB and plotted. Then the best results can be selected from the plot.

$$C^{+}_{(10)(20)} = -\frac{4}{9R}\frac{2\beta_{10}\beta_{20}a^2 + 2k^2a^2 - 5\pi^2}{a\pi^2\sqrt{\beta_{10}\beta_{20}}} \qquad (5)$$

$$\begin{aligned} \frac{dA_{10}}{dz} &= -j\beta_{10}A_{10} - jC^{+}_{(10)(20)}A_{20} \\ \frac{dA_{20}}{dz} &= -j\beta_{20}A_{20} - jC^{+}_{(20)(10)}A_{10} \end{aligned}, \quad \begin{pmatrix} A_{10} \\ A_{20} \end{pmatrix}\Bigg|_{z=0} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad (8)$$

where A_{10}, A_{20} denote complex amplitudes of the TE_{10} and TE_{20} modes, respectively, $C^{+}_{(10)(20)} = C^{+}_{(20)(10)} = C$ describes the coupling coefficients between the TE_{10} and TE_{20} modes. By solving (8), it gives the power amplitudes of output modes at the end of the bend transmission line

$$|A_{10}|^2 = 1 - \frac{C^2\sin^2(\Omega R\theta)}{\Omega^2} \quad |A_{20}|^2 = \frac{C^2\sin^2(\Omega R\theta)}{\Omega^2} \qquad (9)$$

where $\Omega = \sqrt{C^2 + \xi^2}, \xi = (\beta_{20} - \beta_{10})/2$.

```
% cutoff frequency for TE10
f_cutoff_TE10 = (c/(2*pi))*sqrt((m1*pi/width)^2+(n1*pi/height)^2);
% cutoff frequency for TE20
f_cutoff_TE20 = (c/(2*pi))*sqrt((m2*pi/width)^2+(n2*pi/height)^2);
beta = w/c;
f = f_target;
R = linspace(0,250E-3,1000);
k = 2*pi*f/c;

% propagation constant f>f_cutoff
betaTE10 = k.*sqrt(1-(f_cutoff_TE10./f).^2);
betaTE20 = k.*sqrt(1-(f_cutoff_TE20./f).^2);
% mode coupling coefficient
C_10to20 = (-4./(9.*R))...
    .*(2.*betaTE10.*betaTE20*width^2+2.*k.^2*width^2-5*pi^2)...
    ./(width*pi^2*sqrt(betaTE10.*betaTE20));
figure(2)
plot(R/(1E3),real(C_10to20));

ks = (betaTE20-betaTE10)/2;
Omega = sqrt(C_10to20.^2+ks.^2);

Efficiency_TE10 = abs(1-((C_10to20.^2).*(sin(Omega.*(R.*BendAngle)).^2))./(Omega.^2)).^2;
Efficiency_TE20 = abs(((C_10to20.^2).*(sin(Omega.*(R.*BendAngle)).^2))./(Omega.^2)).^2;
```

Figure 13 Formulas and code snippet used for a single bend 90 degree angle simulation.

Propagation Constants

In order for both modes of interest to propagate through the wave guide. The simulation the excitation frequency needs to be above the cut off frequency for both modes. This is shown in figure 13. The simulations that are done from here on out are done at 15GHz because the waveguide dimensions were changed to show that a good conversion efficiency can be achieved at frequencies different than what the reference paper used.

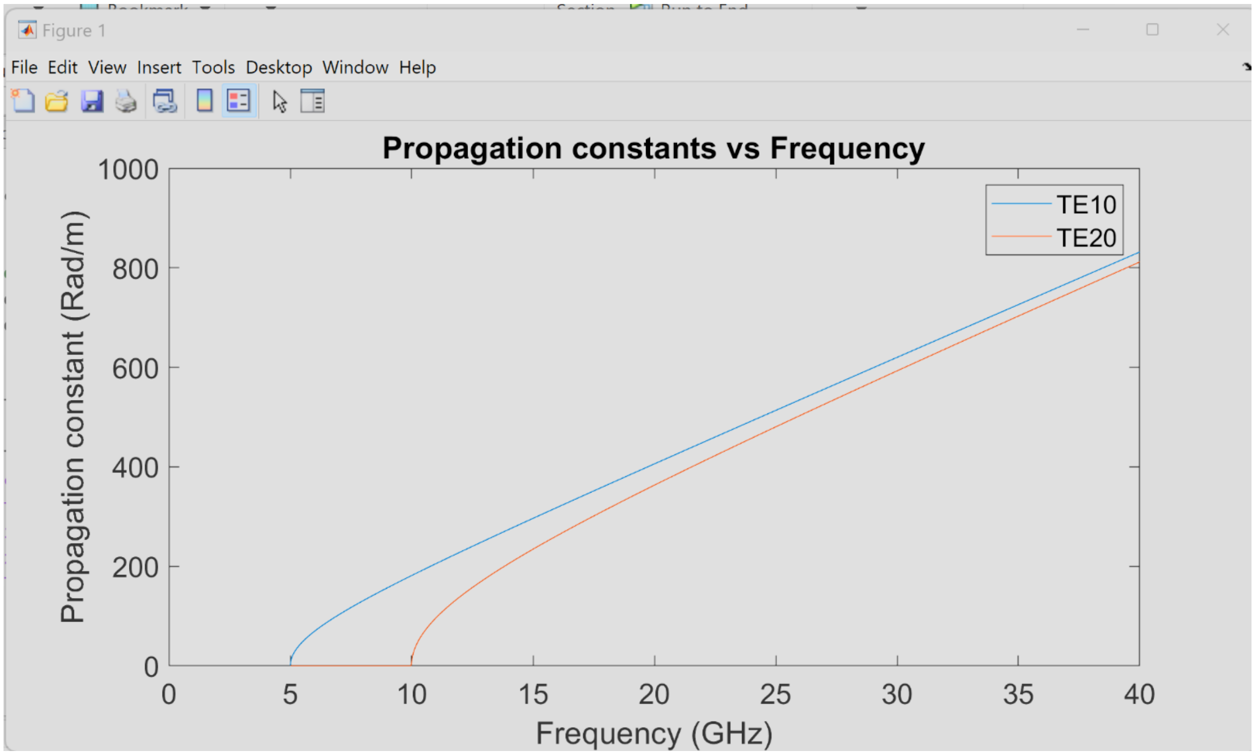

Figure 14 The simulation here uses a 15 by 30 mm rectangular waveguide.

Single Bend 90 Degree Bend Angle Mode conversion Efficiency vs Bend Radius

MATLAB is used to plot the formulas shown in figure 13. The results are shown in figure 15 shows that a bend radius of 65mm or 160mm with give a good conversion efficiency. Figure 16 shows the E field simulation from above validating the results from Figure 15. It shows that the parameters from the paper and the MATLAB plot are in agreement with each other.

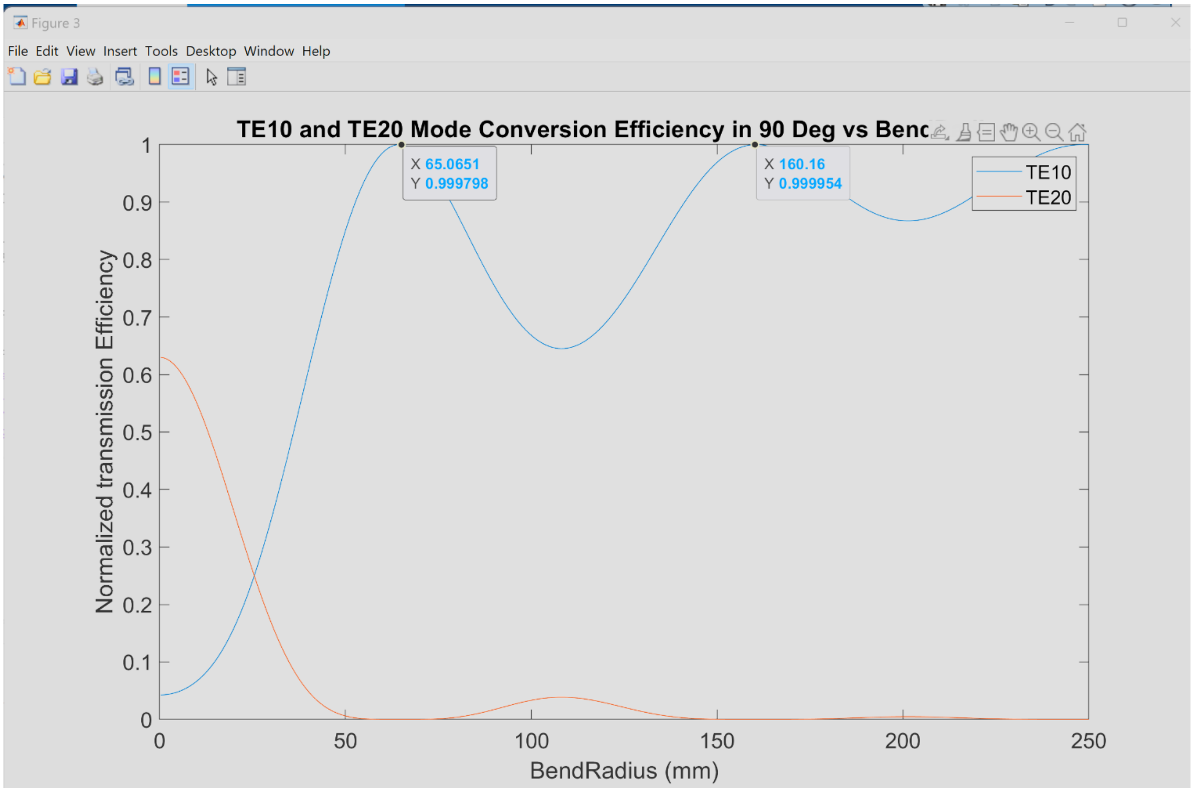

Figure 15 TE20 to TE10 mode efficiency vs bend radius.

Here are the configuration parameters for Figure 16.

- Results – Decent conversion
- TE10 to TE20 bottom to right
- Bend Radius: 65 mm
- Bend Angle: 90 Degrees
- Simulation Frequency: 9.5GHz
- Dimensions: 47.55x22.15 mm

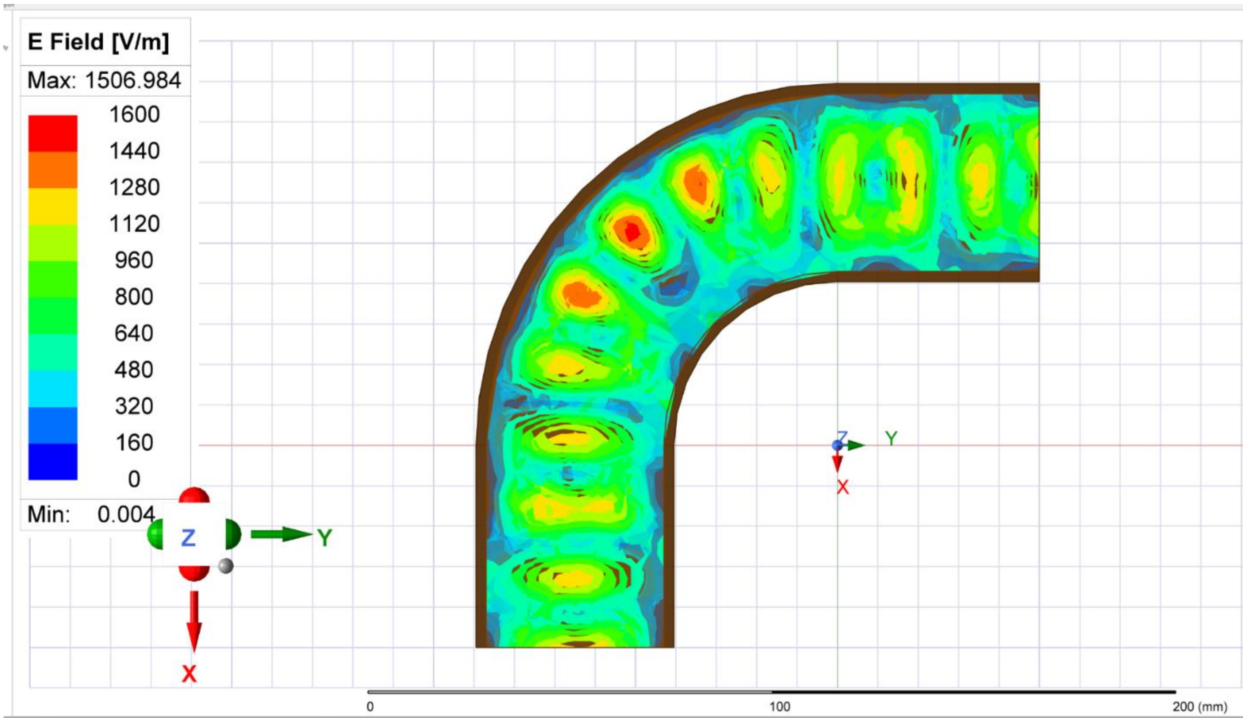

Figure 16

MATLAB Solutions for a Triple Bend Waveguide

This time I used plotted the formulas for a tiple ben waveguide. I also swept the bend angle and the bend radius to get better optimization results.

- TE10 to TE20 from bottom to top
- Bend Radius: 66 mm
- Bend Angle: 120 Degrees
- Simulation Frequency: 15GHz
- Dimensions: 15x30mm

Figure 18 shows good results when the bend radius is 66 degrees, and the bend angle is 120 degrees. Figure 19 shows the simulated results and it looks okay, but it probably wasn't as good be cause of how sensitive the bend radius and bend angle are as shown in figure 18.

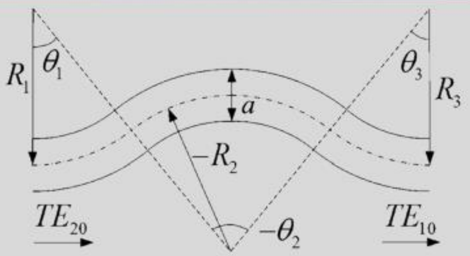

Fig. 14. Geometry sketch of the tri-bend TE_{20}–TE_{10} rectangular waveguide mode converter.

$$T = \frac{16\alpha^2 R^4 \xi^4}{(\alpha^2 + R^2\xi^2)^3} \times \sin^4\left(\sqrt{\alpha^2 + R^2\xi^2}\theta\right)\sin^2\left(2\sqrt{\alpha^2 + R^2\xi^2}\theta\right). \quad (15)$$

Then observe (16) and (17), shown at the bottom of this page, where $\zeta = \sqrt{\alpha^2 + R^2\xi^2}\theta$.

```
betaTE10 = k*sqrt(1-(f_cutoff_TE10/f)^2);
betaTE20 = k*sqrt(1-(f_cutoff_TE20/f)^2);

% mode coupling coefficient
C_10to20 = (4/(9))...
    *(2*betaTE10*betaTE20*width^2+2*k.^2*width^2-5*pi^2)...
    /(width*pi^2*sqrt(betaTE10*betaTE20));

ks = (betaTE20-betaTE10)/2;

indexSize = 10;
Angle = linspace(0,pi,indexSize);
Legend=cell(indexSize,1);

for i=1:indexSize
    ks1 = sqrt((C_10to20^2)+R.^2.*ks^2)*Angle(i);

    Efficiency = (16*C_10to20^2.*(R.^4).*(ks^4)./...
        ((C_10to20^2+R.^2.*ks^2).^3)).*(sin(ks1).^4).*sin(2.*ks1).^2;
    figure(3)
    plot(R*1E3,Efficiency);
    hold on
    disp([num2str(i),' ',num2str(Angle(i)*180/pi)]);
    Legend{i}=strcat(num2str(Angle(i)*180/pi),' Deg');
end
```

Figure 17 Formulas and code snippet for a triple bend waveguide.

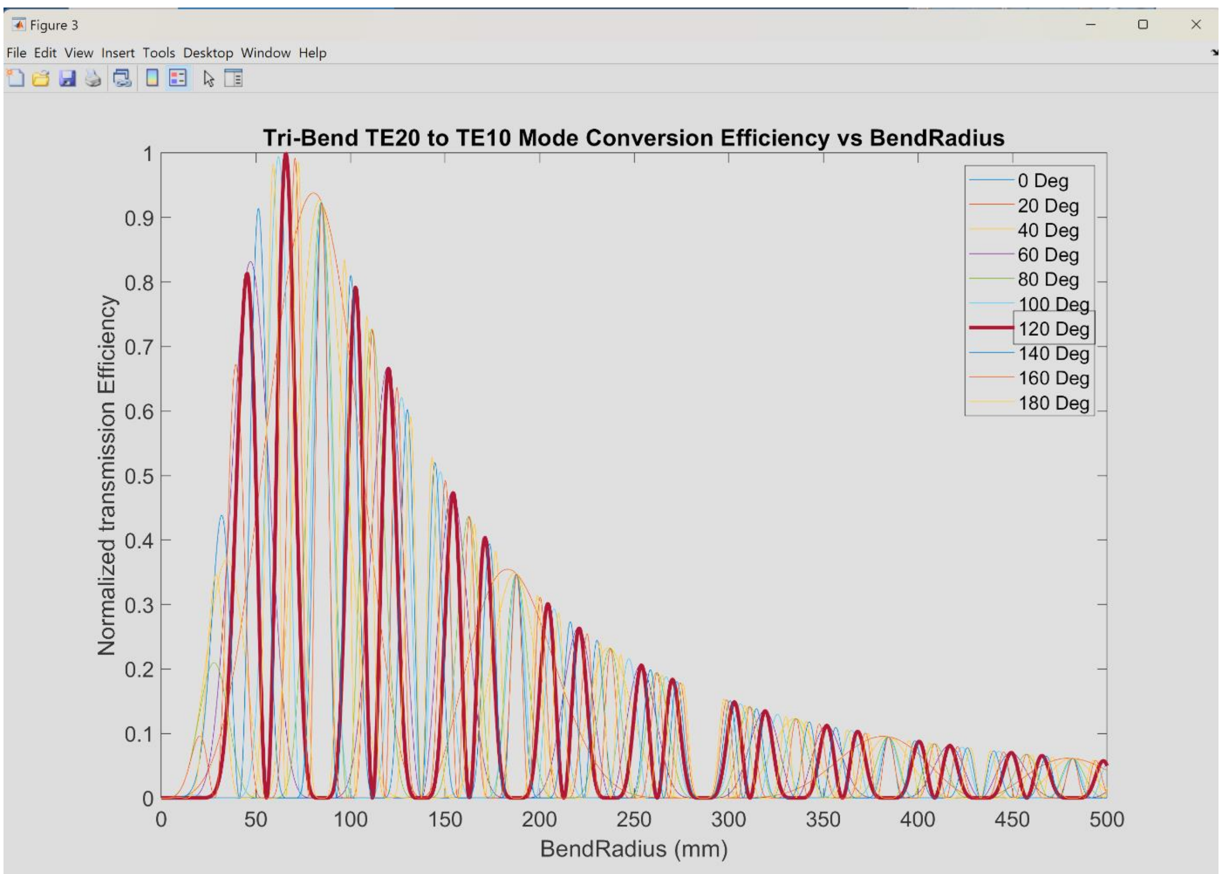

Figure 18 Results from MATLAB plot.

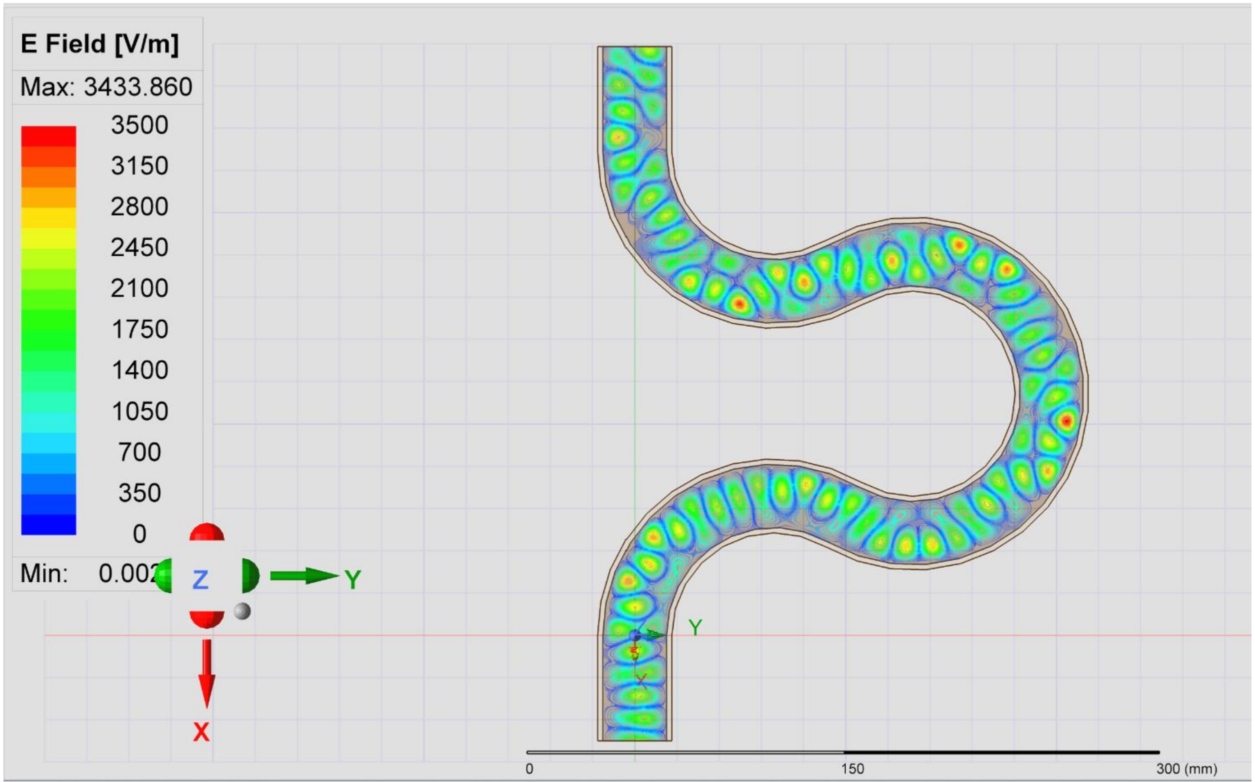

Figure 19

To fix the sensitivity issue from figures 18 and 19. The dimensions were modified as shown in the list below. Now figure 20 shows good results that are not as sensitive.

- TE10 to TE20: Bottom to Top (Left)
- TE20 to TE10: Top to Bottom (Right)
- Bend Radius: 113mm
- Bend Angle: 20 Degrees
- Simulation Frequency: 15GHz
- Dimensions: 15x35mm

Figures 21 and 22 show that the calculated simulations are a success and provide maximum conversion efficiency as the formulas predicted. The mode converters are also symmetric which is why figures 21 and 22 both work. Figure 23 shows the conversion efficiency vs frequency and it is near a maximum at the desired frequency of 15GHz.

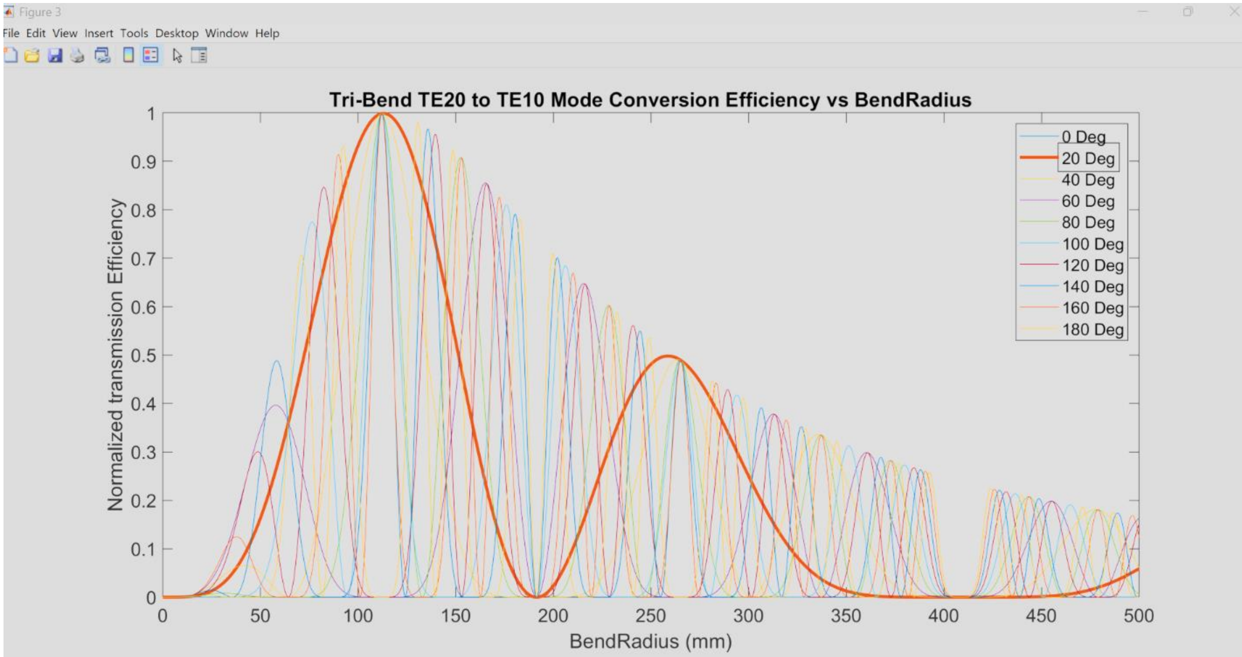

Figure 20

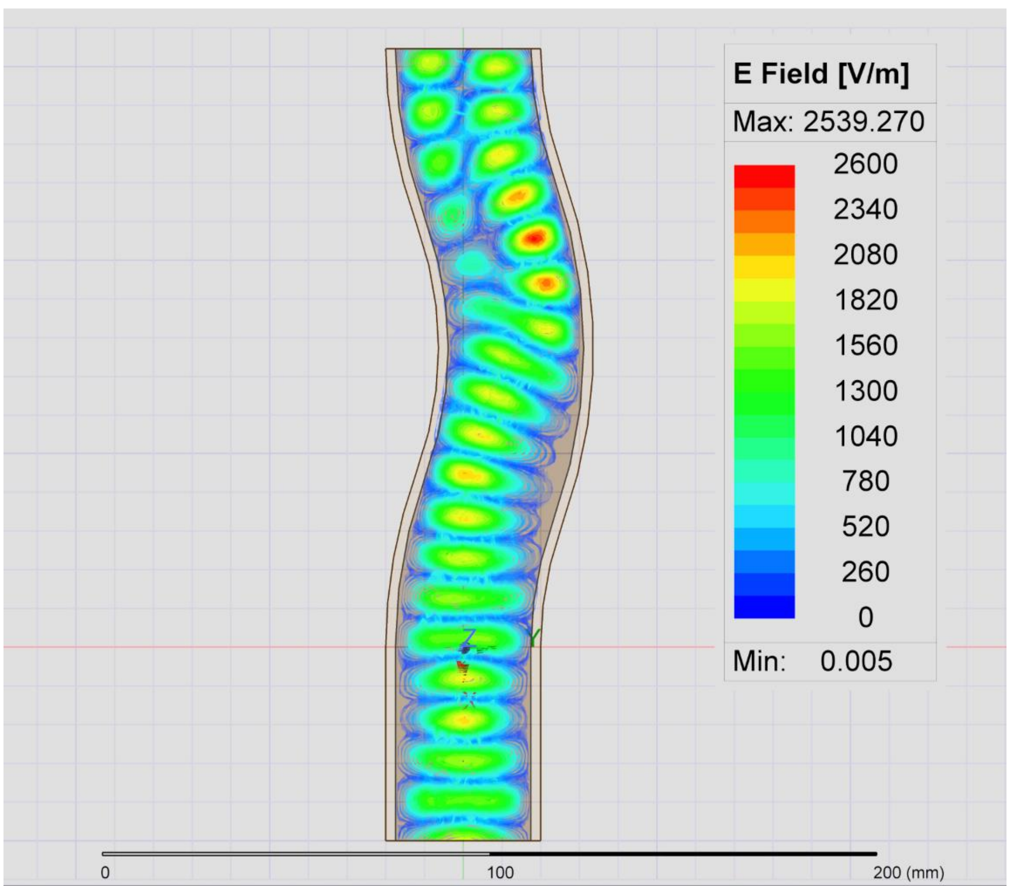

Figure 21

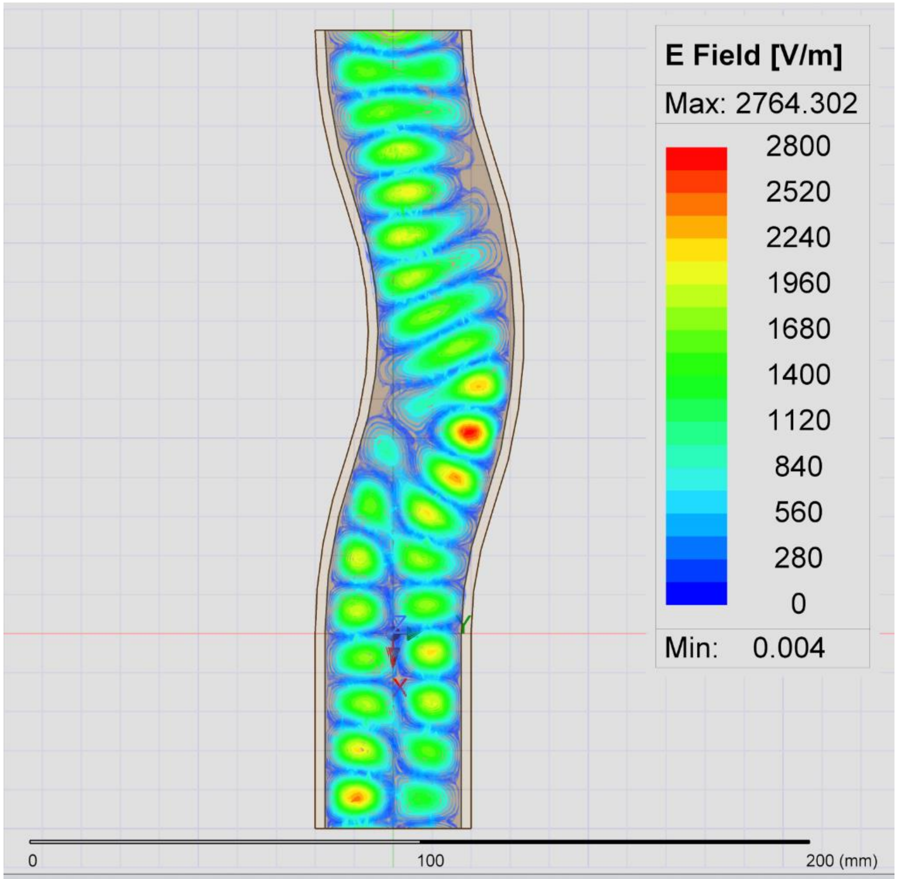

Figure 22

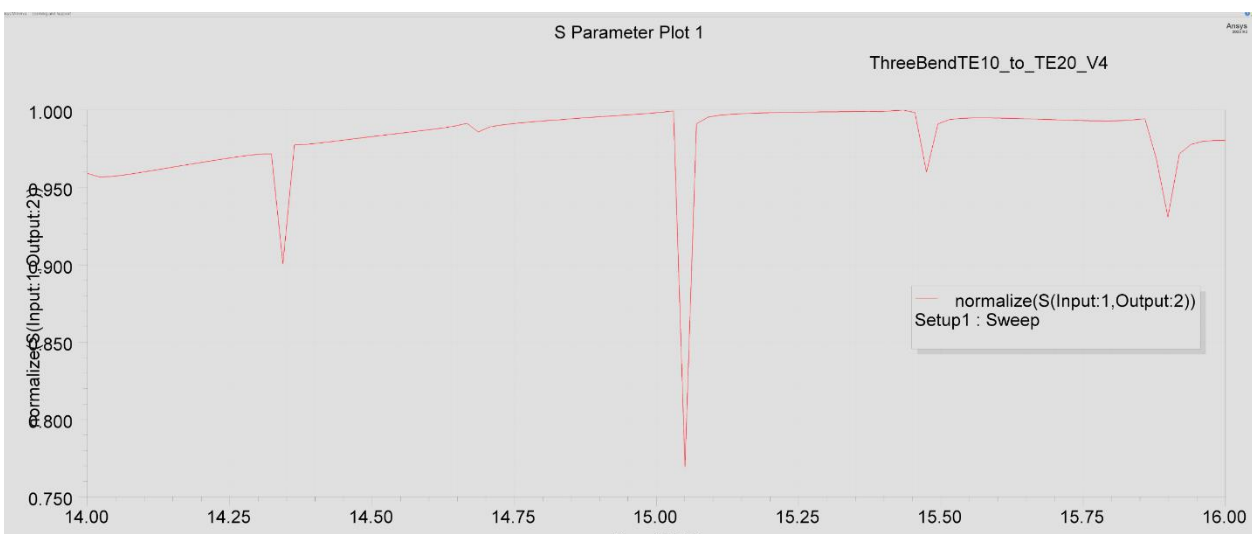

Figure 23

Conclusion

I was able to improve my Ansys skills and I learned that using the optimization tool in Ansys is difficult. I was able to build a TE10 to TE20 converter at a chosen frequency using the formulas. I also developed a generalized way of designing waveguide mode converters. I didn't have time to experiment with power combiners, but that shouldn't be too difficult because all the individual pieces can be built and combined later. This was a rewarding project and my understanding of waveguide conversion has deepend.

References

The paper I chose to use is called "Theoretical Design and Analysis for TE20– TE10 Rectangular Waveguide Mode Converters" which can be found in the technical journal IEEE Transactions on Microwave Theory and Techniques Volume: 60 Issue:4. The main authors are Qiang Zhang, Cheng-Wei Yuan, and Lie Liu.