2020

Improving The Efficiency of Planar Goubau Line and Goubau-Line-Based Endfire Antenna

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ABSTRACT

IMPROVING THE EFFICIENCY OF PLANAR GOUBAU LINE AND GOUBAU-LINE-BASED ENDFIRE ANTENNA

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Northern Illinois University, 2020

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This thesis presents the use of two dielectric layers in a planar Goubau line (PGL) to improve its transmission efficiency compared to the existing single-layer models, which is less than 70% efficient at lower frequencies up to 5 GHz. Further, as an extension of the thesis, the possibility of obtaining directive radiation pattern with radiation efficiency greater than 89.6% using a Goubau-line-based antenna is studied. While none of the existing Goubau-line-based antennas are able to obtain an endfire pattern with radiation efficiency of above 80%, the proposed model utilizes stubs that are periodically attached to the main line of length $0.75\lambda_c$ to obtain an endfire radiation having a radiation efficiency of 93% and a forward gain of 6.5 dBi while operating at a frequency of 3 GHz. The performance of the proposed PGL and antenna design are evaluated by simulations using CEMS electromagnetic simulation software.

***Keywords**:* planar Goubau line; end-fire radiation pattern; radiation efficiency

NORTHERN ILLINOIS UNIVERSITY

DEKALB, ILLINOIS

MAY 2020

IMPROVING THE EFFICIENCY OF PLANAR GOUBAU LINE AND GOUBAU-LINE-BASED ENDFIRE ANTENNA

BY

SREELAKSHMI RADHAKRISHNAN

A THESIS SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

Thesis Director:

Dr. Veysel Demir

ACKNOWLEDGEMENTS

"I am grateful to God for all the blessings."

I would like to express my sincere gratitude to Dr. Veysel Demir for his continued support and guidance in completing this thesis. He has been extending great advocacy and encouragement in the completion of this thesis. Furthermore, I would also like to extend my sincere gratitude towards my advisory committee, Dr. Donald S. Zinger and Dr. Benedito Fonseca, for their constant support throughout my thesis work.

I would like to thank my parents for their prayers and continuous support. I would like to thank my husband, who has always encouraged me to pursue my dreams no matter what the challenges are.

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LIST OF ACRONYMS

CEMS: Computational Electromagnetics Software

CPW: Coplanar Waveguide

FDTD: Finite Difference Time Domain

LWA: Leaky Wave Antenna

PGL: Planar Goubau Line

S Parameters: Scattering Parameters

SWTL: Surface Wave Transmission Line

TEM: Transverse Electromagnetic

TM: Transverse Magnetic

UHF: Ultra High Frequency

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Single-wire transmission line (SWTL) is a type of transmission line which utilizes the guided surface waves along a single isolated conductor [1]. This contrasts with the usual electrical cable containing at least two conductor wires to form a complete circuit. Although the metallic shielding is not present in these lines, the propagating signals stay tightly bounded to the proximity to the conductor, hence does not radiate along the line, allowing for much lower losses compared to coaxial cables and other two-wire lines. The boundary layer combined with imperfections in the conductor surface is responsible for supporting the surface wave.

In order to excite the desired wave mode with high transmission efficiency, a launching device is needed [2]. The launcher is necessary to excite the proper fields for surface wave formation as well as to transform the impedance from the coaxial port, which is 50 Ohms, to that of the single conductor, which is around 200 Ohms [3]. Goubau lines can serve as low-loss antenna feedlines [4] at upper end of UHF frequencies, up to microwave frequencies where a waveguide must be used.

1.2 PROBLEM DESCRIPTION

Planar Goubau line (PGL) with its compact size is preferred over the microstrip line due to its lower losses. The PGLs usually have a single dielectric layer and have shown great performance mainly in the terahertz frequency range [5]. But none of the existing PGL models provide an effective method to improve the transmission efficiency at the lower frequencies, which is less than 70% efficient for frequencies up to 5 GHz. Hence the primary objective of this thesis is to reduce the losses in PGL at lower frequencies by using two dielectric layers and thereby increasing the overall transmission efficiency of the line to 90%.

Further, as an extension of the thesis, the possibility of obtaining directive radiation pattern with a radiation efficiency greater than 90% using a Goubau-line-based antenna is studied. Since none of the existing Goubau-line-based antennas can provide a directive pattern with over 70% radiation efficiency, the proposed model aims at improving the radiation efficiency and directivity of the radiation pattern with reduced antenna size.

1.3 OVERVIEW

In the rest of this thesis, Chapter 2 discusses the existing literature on Goubau lines and Goubau-line-based antennas. Chapter 3 provides an overview of the proposed two-layer Goubau line design and optimization procedures. Chapter 4 provides an overview of the proposed Goubau-line-based antenna with directive pattern, optimization procedures, and design considerations. Simulation results of both transmission line and antenna design are discussed in Chapter 5. Finally, Chapter 6 summarizes the thesis and discusses future research opportunities.

CHAPTER 2

LITERATURE REVIEW

This section gives an overview of the existing literature on Goubau lines, which is a type of single-wire transmission line. The evolution of planar Goubau line in terahertz frequency range and their applications in the leaky wave antenna designs are also discussed here along with the recent advances in the area of Goubau line studies.

2.1 GOUBAU LINE

Sommerfled in 1899 for the first time suggested the possibility of a nonradiating wave propagating along an infinitely long cylindrical metal wire with finite conductivity. Later, in 1950, Goubau [1] experimentally verified that the surface waves can be excited with high transmission efficiency on a single wire coated with a dielectric layer; hence, SWTL is also called Goubau line. Goubau [2] suggested that the best results are obtained for launcher design when coaxial section has a large diameter and the inner conductor is tapered down until it approximately matches the diameter of the surface-wave conductor.

At first Goubau line was used for feeding transmitting aerials [4] and later as a single-wire radio frequency transmission line in biological tissues [6]. Recently Goubau line has been used in testing beam instrumentation at high frequencies [7] and Goubau line-based antenna has been implemented in security fence radars [8].

In order to excite the guided surface waves, Goubau line needs launchers as shown in Figure 1 that convert the TEM mode of a coaxial port into TM mode supported by the line [1]. The launcher also functions as an impedance matching network between the coaxial port to the wire and vice versa. Radiation from launchers and bends in the line contribute to the major losses in Goubau line. Hence the design of launchers and line plays an important role in improving the transmission efficiency and quality [9].

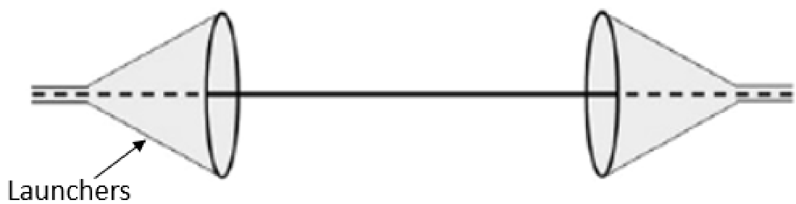


Figure 1. Goubau line [8].

2.2 PLANAR GOUBAU LINE

Over the last decade it has been found that the conducting wires on a planar dielectric substrate can propagate terahertz (THz) waves in the same way as a Goubau line [5]. The excitation of planar Goubau line was made possible with a coplanar waveguide (CPW) transition as shown in Figure 2, fed with a THz signal onto a tapered line, and was able to achieve a transmission efficiency up to 75% over a broad frequency range. The reflection parameter (return loss) is less than -10 dB over a broad frequency range and the insertion loss level is -2.5 dB at 180 GHz.

PGL is used to connect two points in a short path and therefore can be used in THz power divider circuit [10] and in biosensors [5]. Although the transmission efficiency of PGL at lower frequencies is considerably low, the PGL-based antennas are found to have lower losses compared to the widely used microstrip antennas.

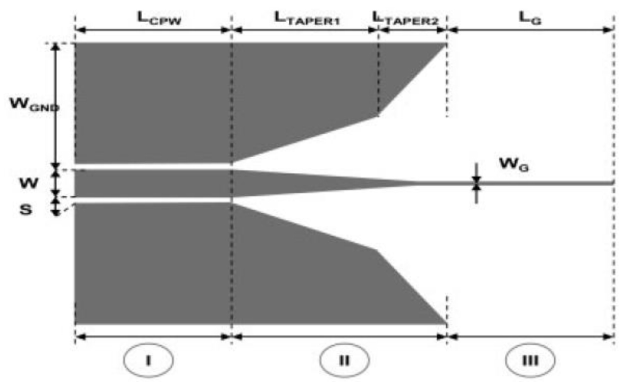


Figure 2. Planar Goubau line excitation structure [5].

2.3 GOUBAU-LINE-BASED LEAKY WAVE ANTENNA

Microstrip antenna with its low profile, low weight, compact design and useful practical application is one of the most studied structures. However, high concentration of electric field in the dielectric substrate results in a low radiation efficiency in microwave antennas. The elimination of ground plane can reduce the confinement of field in the dielectric layer, which also reduces both dielectric and ohmic losses. The resulting structure is a PGL with a nonradiating surface wave mode [11]. In order to make the PGL radiate, periodic discontinuities need to be introduced in the line. The resulting antenna is called a Goubau-line-based leaky wave antenna (LWA). LWA usually has an omnidirectional radiation pattern.

The periodic Goubau line LWA [11] as shown in Figure 3 radiates by generating leakage that is produced by adding dipoles along the line on the bottom face of the substrate. The resulting structure radiates in two symmetric directions due to the absence of a ground plane. To confine the energy in one direction, the use of a reflector plane not connected to the ground plane of the coplanar waveguide is utilized, and higher radiation efficiency than in microstrip-fed antennas was achieved. However, the maximum radiation efficiency achieved was limited to 71% even at a high frequency of 40 GHz.

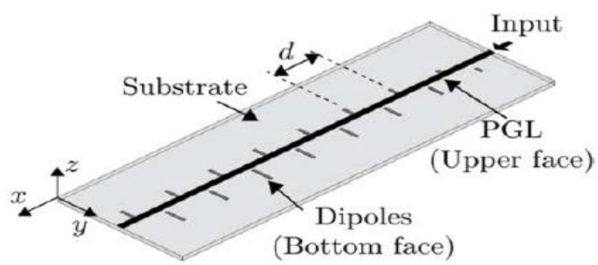


Figure 3. Configuration of periodic LWA with dipoles along bottom surface [11].

The LWAs usually suffer from a low radiation efficiency at the broadside direction. To overcome this problem the asymmetrically modulated Goubau line LWA [12] employs both transversally and longitudinally asymmetrical modulations to the Goubau line as shown in Figure 4 and was able to obtain a continuous beam scanning from the backward direction to the forward direction through the broadside within 9-13 GHz, with an omnidirectional radiation pattern and a radiation efficiency above 70%.

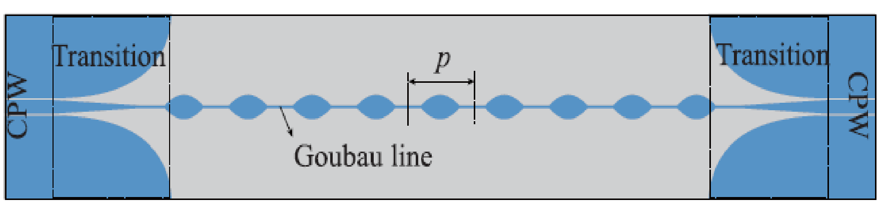


Figure 4. Configuration of sinusoidally modulated periodic LWA based on Goubau line [12].

The reconfigurable Goubau line-based antenna [13] shown in Figure 5 consists of a series of patches and switches along the Goubau line. These periodic elements are placed in a distance G away from the Goubau line and are employed to produce the radiations. The reconfigurable performance of the main beam angles of the antenna depends on the ON or OFF state of switches. This LWA has an electronically steerable main beam with an omnidirectional radiation pattern at frequency ranging from 8.5 GHz to 9 GHz.

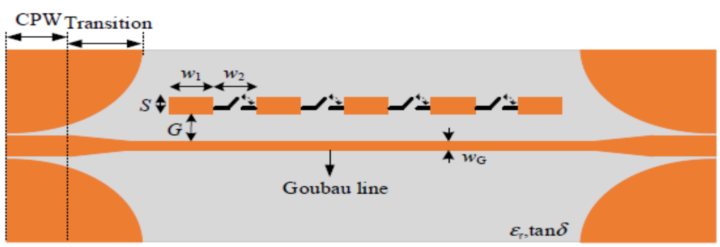


Figure 5. Configuration of reconfigurable LWA based on Goubau line [13].

In the LWA design [14], a Goubau-line based LWA with a large scanning angle is obtained from perturbations that are formed by periodically bending the line as shown in Figure 6. The LWA provides 90% radiation efficiency and 7–10 dBi radiation gain from backfire to endfire through broadside as frequency changes. However, the radiation efficiency for this LWA below 5.5 GHz is less than 50%.

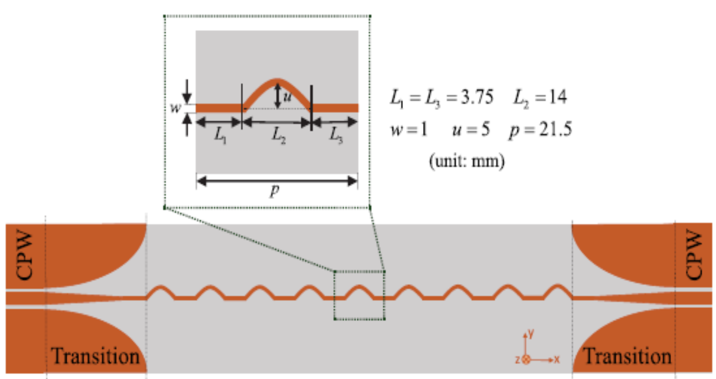


Figure 6. Configuration of Goubau line LWA with large scanning angle [14].

In the LWA design [15] as shown in Figure 7, glide symmetry is utilized for achieving both high scanning rate and scanning angle range. The LWA exhibits dual band operation, where one band scans 152 degrees within 2.2 GHz for a scanning rate of 69 degrees/GHz with 67% radiation efficiency, and the second band scans 145 degrees within 0.7 GHz for a scanning rate of 207 degrees/GHz with 26%.

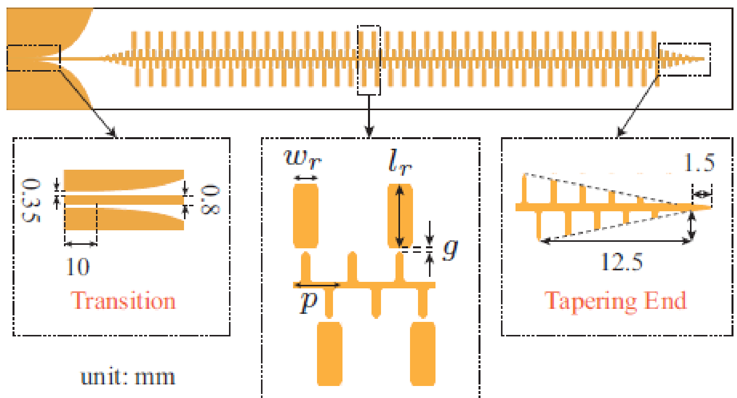


Figure 7. Configuration of LWA based on glide-symmetry Goubau line [15].

Recently the Goubau-line-based endfire antenna [16] achieves an endfire radiation by adding periodic arrangements of V-shaped unit cells shown in Figure 8. The LWA radiates towards forward direction at 7.8 and 8.3 GHz with a maximum gain of 7.2 dB and the average radiation efficiency is over 70% over the entire operating frequency range. Though the design succeeds in obtaining high gain, the overall size of the design is too large.

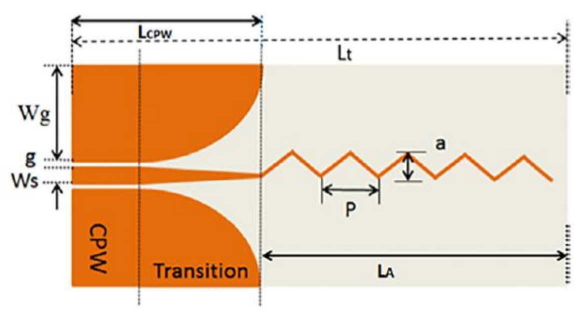


Figure 8. Configuration of Goubau-line-based endfire antenna [16].

CHAPTER 3

TWO-LAYER GOUBAU LINE

This section discusses the procedure used for designing two-layer Goubau line for obtaining improved reflection coefficient and thereby improving the overall transmission at lower frequencies up to 5 GHz. Following are the steps to design the proposed Goubau line.

1. Design of PGL with single dielectric layer as shown in Figure 9.

   i. Design the CPW structure using SONNET and optimize the design to achieve S_{11} below -10 dB.

   ii. Simulate the circuit in CEMS, which is an electromagnetic simulation software based on the FDTD method.

   iii. Estimate the transmission efficiency of the transmission line as follows:

   For a lossless two-port network, $|S_{11}|^2 + |S_{12}|^2 = 1$.

   Since the circuit is reciprocal, $S_{ij} = S_{ji} \Rightarrow S_{12} = S_{21}$, where S_{11} and S_{21} are the scattering parameters and defined as follows:

   S_{11} → Input reflection coefficient due to mismatch in source impedance with the characteristic impedance.

   S_{21} → Measure of amount of power transmitted to port 2 from port 1. Therefore, transmission efficiency = $|S_{11}|^2 + |S_{21}|^2$.

iv. Add a partial ground plane on both sides of the line to connect the coplanar ground plates.

v. Simulate the circuit in CEMS by varying the length of ground to find the optimum dimension to achieve maximum transmission efficiency.

vi. Simulate design in CEMS with different dimensions of CPW transitions and tapering to find the optimum dimension to achieve maximum transmission efficiency.

vii. Simulate design in CEMS for different values of thickness and dielectric constants of the substrate to achieve maximum transmission efficiency.

2. Design of two-layer Goubau line.

i. Add a dielectric layer with the same dielectric constant on top of the optimized PGL.

ii. Simulate the circuit in CEMS and estimate the transmission efficiency.

iii. Compare the transmission efficiency of both models along with the S_{11} and S_{21}.

Only the design part is discussed in this chapter. The simulation results are discussed in detail in Chapter 5, Section 5.1.

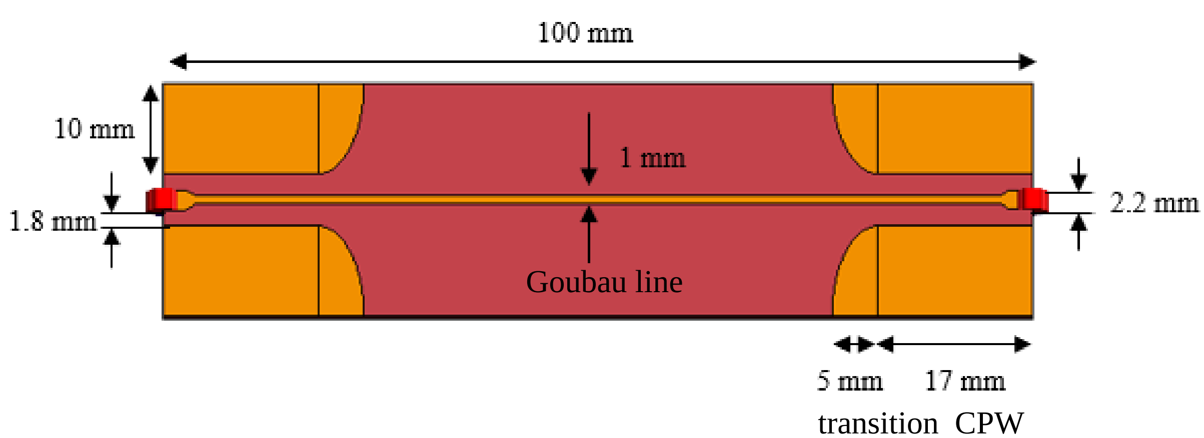


Figure 9. Configuration of metal layer in the proposed Goubau line.

3.1 COPLANAR WAVEGUIDE DESIGN

In planar Goubau line, CPW acts as launcher that also functions as an impedance matching network between the coaxial port to the Goubau line and vice versa. Since radiation from launchers and bends in the line contribute to the major losses in Goubau line, the design of CPW plays an important role in improving the transmission efficiency and quality, and therefore proper optimization of CPW launcher is crucial.

Initially the CPW without ground plane was designed using AppCAD [17] with a dielectric constant of 2.2 as shown in Figure 10. AppCAD is a design assistant software for RF, microwave, and wireless applications.

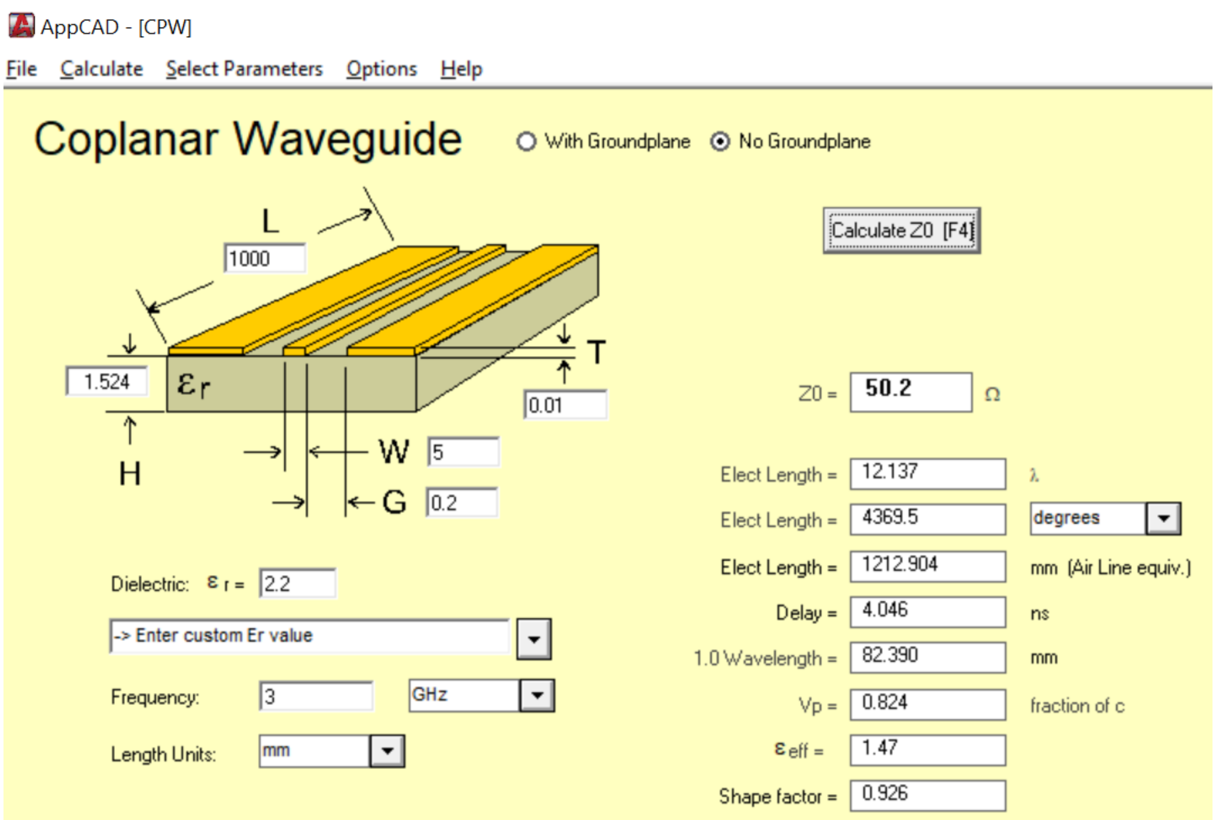


Figure 10. Coplanar waveguide design in AppCAD.

Since the dimensions obtained for the gap was too small and might cause issues while fabrication, such a design is not appropriate and hence the design was modified by adding a partial ground plane. Later the length of the partial ground plane was gradually reduced to obtain optimized values for S parameters. Finally, a partial ground plane of length 0.5 mm was added at the bottom layer at both ends connecting the CPW ground planes on the top.

The width of the transmission line and the gap between the ground plates on the top layer were optimized to achieve the value of S_{11} below -10 dB; the optimization was done using SONNET, which is an electromagnetic simulation software. Metal layer was designed as perfect electric conductors. The length of the line considered is 3λ. The transmission line is tapered to a width of 1 mm for proper excitation of surface waves.

The tapering of the transmission line and the length and transition of the coplanar waveguide was varied to improve the values of S_{11} and S_{21} parameters. S_{11} was reduced by extending the CPW and S_{21} was improved by increasing the tapering and CPW transition. The position of tapering was gradually changed w.r.t. CPW transition to find the optimum distance for obtaining lower losses. Tapering of the line closer to the CPW transition increased the return loss. Hence tapering position was finalized to be near the CPW extension part for lower S_{11} and higher S_{21}.

3.3 SUBSTRATE LAYER

Initially the substrate layer considered for the design was of low dielectric constant of value 2.2 and height 1.524 mm. Later the value of dielectric constant was gradually increased to analyze its impact on S_{11} and S_{21} and finally fixed at a high value of 10.2. Higher value of dielectric constant reduces the phase velocity of the wave and hence the surface wave will be more tightly bounded.

The simulation is repeated by placing the same substrate over the metal layer, resulting in a sandwich structure as shown in Figure 11 and Figure 12(b). Adding a dielectric layer on the top of the metal layer can further reduce the phase velocity of the wave holding the surface wave more tightly bounded to the line, which in turn improves S_{21} and hence the transmission efficiency. Finally, this theory was verified by simulating the design over the same frequency range and comparing the results with that of single-layer PGL, which is discussed in Chapter 5.

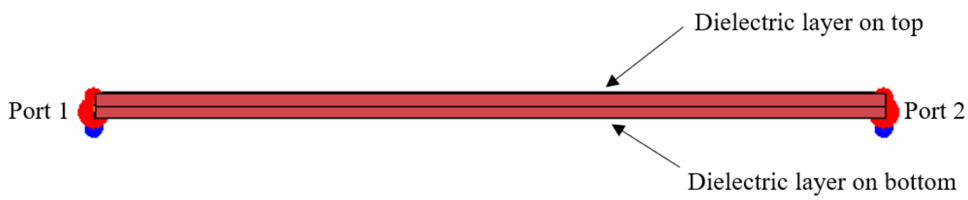


Figure 11. Side view of the proposed two-layer Goubau line.

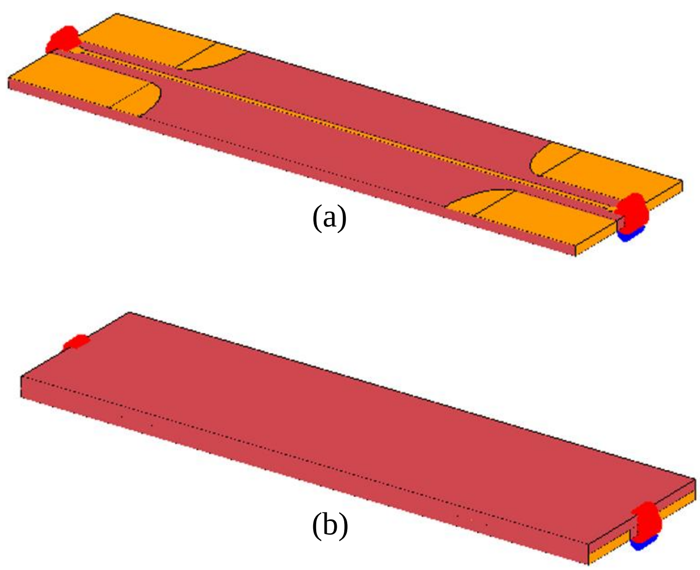


Figure 12. Two-layer Goubau line. (a) Before adding dielectric substrate on top of single-layer PGL. (b) Proposed Goubau line: dielectric layer is added on top of single-layer PGL.

CHAPTER 4

GOUBAU-LINE-BASED ENDFIRE ANTENNA

An efficient planar Goubau line operates in nonradiative surface wave mode. In order to make the PGL radiate, periodic discontinuities need to be introduced in the line [11]. The resulting antenna is called a Goubau-line-based leaky wave antenna (LWA). LWA usually has an omnidirectional radiation pattern and a radiation efficiency below 70%.

In this chapter, an antenna is proposed which utilizes the Goubau line design in Chapter 3, but with reduced length onto which stubs are periodically added in order to obtain a strong radiation pattern in the forward direction at frequency of 3 GHz. The design is simulated in CEMS with substrate having high dielectric constant of 10.2.

Antenna design with directive pattern is particularly useful because it enables all the transmitted power to be directed into the area where it is required, or when used for reception, it enables the maximum signal to be received from the same area. Coupled to this is the fact that it has reduced gain in other directions, which means that it receives or transmits less signal in other directions, thereby reducing the levels of interference.

Though the Goubau-line-based endfire antenna [16] utilizing the periodic arrangements of V-shaped unit cells as shown in Figure 8 has achieved an endfire pattern with a maximum gain of 7.2 dB and an average radiation efficiency of over 70%, the length of the antenna is about 2.9 λ_c,which is much longer compared to a Yagi antenna with similar gain.

4.1 DESIGN OF LEAKY WAVE ANTENNA

The planar Goubau line in Figure 10 is modified by adding an array of stubs attached to the transmission line in order to make the structure radiating as shown in Figure 13. Stubs were attached to opposite sides of the line alternately so that it can act as a reflector to cancel out the radiation in the backward direction, resulting in a highly directive radiation pattern in the forward direction. Since the antenna design utilizing two dielectric layers was not effective in obtaining a directive pattern, the top dielectric layer was removed.

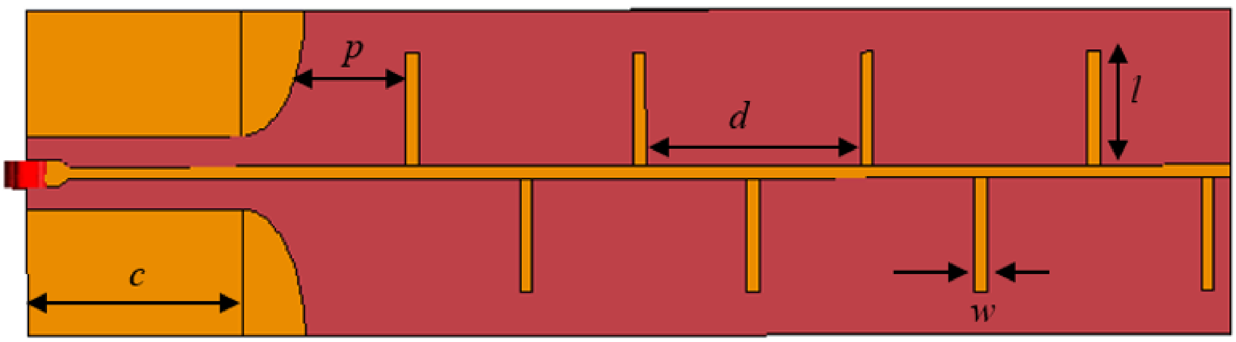


Figure 13. Goubau-line-based antenna with directive pattern.

Though this design was effective in obtaining a directive beam, utilizing the same configuration of Goubau line means that the antenna will have an increased length, which is more than $1\lambda_c$, where λ_c is the wavelength of electromagnetic wave in free space at the design frequency.

In order to reduce the effective length of the antenna, the length of the coplanar waveguide was adjusted such that the impedance matching is not compromised and S_{11} is below -10 dB. Also, the gap between stubs and the position of the first stub was adjusted to obtain a strong radiation along the forward direction. The effective length of the antenna is 0.75 λ_c, which is comparable to the length of similar Yagi-Uda antenna.

Later, a parametric study of the design was done for improving the gain by changing the following parameters:

1) Position of the first stub (*p*)
2) Distance between stubs (*d*)
3) Length of the stub (*l*)
4) Width of the stub (*w*)
5) Length of CPW (*c*)

The gap between the stubs is a significant factor in deciding whether the direction of resulting beam must be forward or backward. It also decides the shape and beam width of the pattern obtained. Reducing the length between elements any further results in a strong radiation in the backward direction. Also, reducing the CPW length results in increasing the return loss, thereby compromising the impedance matching of the design. The results obtained for each parameter are discussed in detail in Chapter 5. The resulting antenna design is shown in Figure 14.

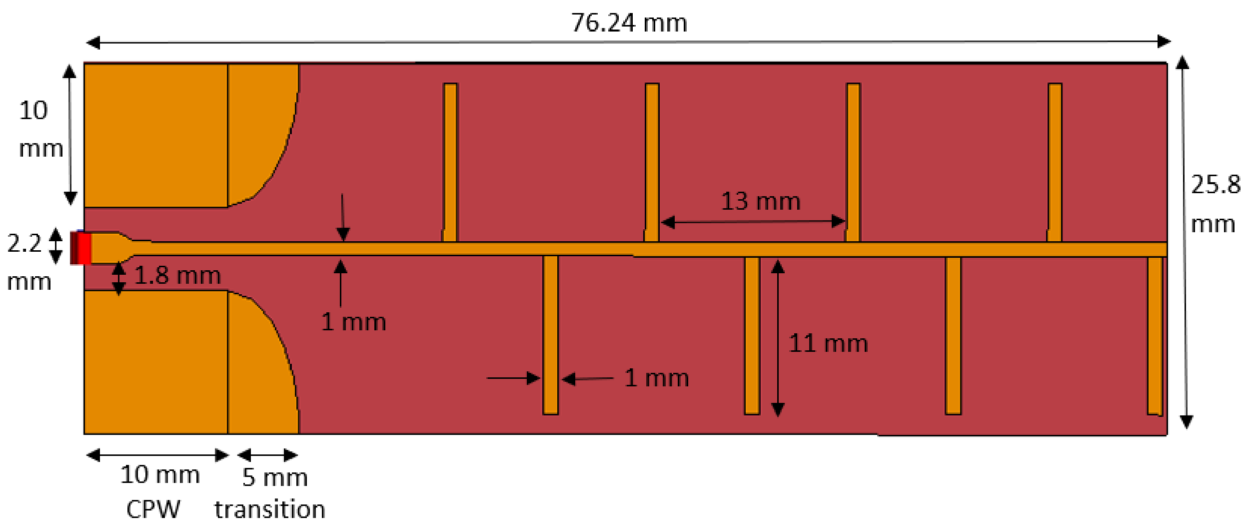


Figure 14. Optimized design of proposed leaky wave antenna.

CHAPTER 5

SIMULATION RESULTS IN CEMS

In this chapter, Section 5.1 discusses the simulation results obtained for the two-layer Goubau line transmission line and compares it with the results obtained for a single-layer model. Section 5.2 presents the radiation pattern and frequency response obatined for the Goubau-line-based antenna with directive pattern.

5.1 TWO-LAYER PGL MODEL SIMULATION IN CEMS

The simulation results of single-layer PGL is shown in Figure 15. It can be noticed that while the return loss (S_{11}) is less than -10 dB over the frequency range of 4.12 GHz to 5.4 GHz, the insertion loss is not consistently greater than -2 dB over this bandwidth. Because of this, the overall transmission efficiency stays below 70%, as shown in Table 1, where Tables 1 and 2 contain the absolute value of S parameters.

From the simulation waveform in Figure 16 it can be noticed that the two-layer Goubau line has value of S_{11} less than -10 dB over the frequency range of 3.45 GHz to 4.7 GHz. Also it can be noticed that the value of S_{21} is greater than -1.5 dB in this frequency range, which is an improvement from the single-layer model.

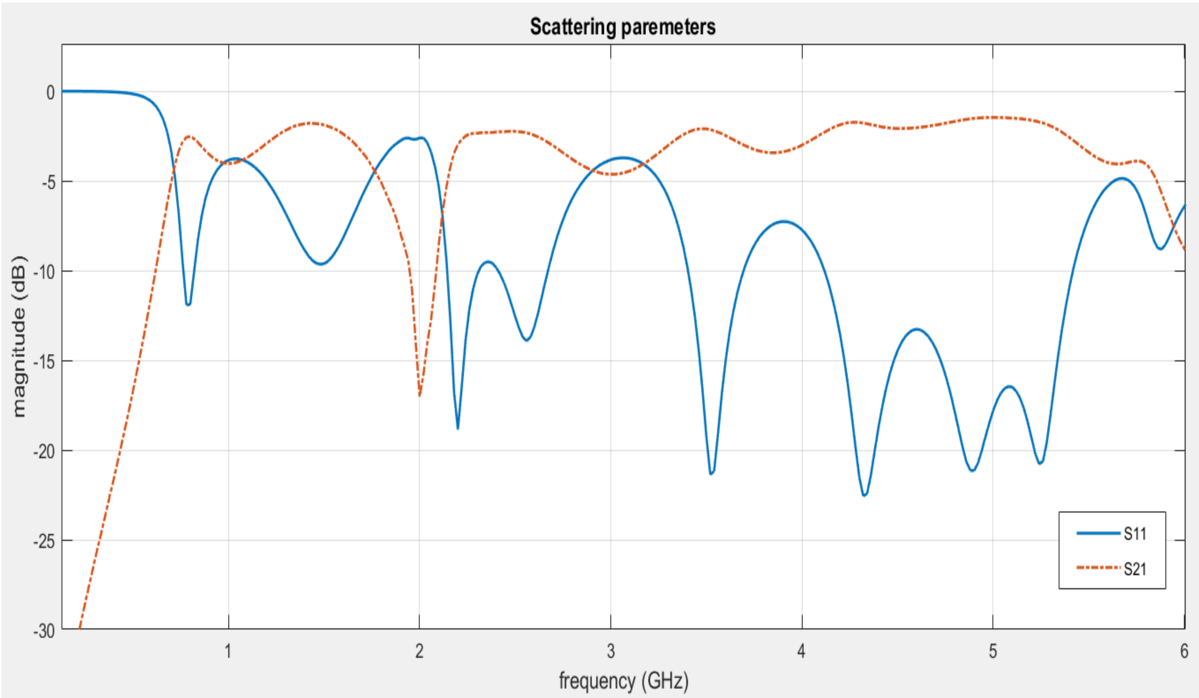


Figure 15 Simulation results of single-layer Goubau line: S_{11} and S_{21} in dB scale.

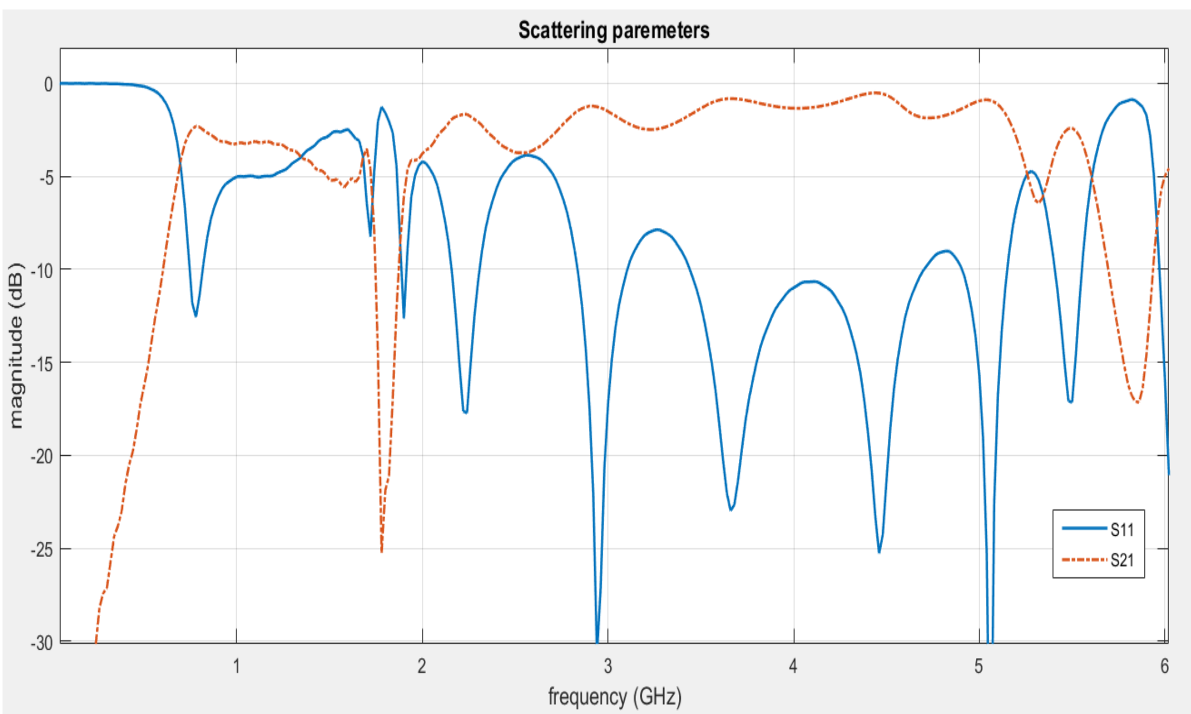


Figure 16. Simulation results of two-layer Goubau line: S_{11} and S_{21} in dB scale.

Table 1. Numerical Data showing transmission efficiency of single-layer Goubau line

Frequency (GHz)	$\mathbf{|S_{11}|}$	$\mathbf{|S_{21}|}$	**Transmission efficiency**
4.16	0.26342	0.79065	62.5 %
4.28	0.12478	0.81864	67 %
4.6	0.21714	0.80814	65.4 %
5	0.12894	0.84482	71.4 %
5.24	0.091359	0.8208	67.4 %
5.28	0.10497	0.80814	65.3 %

Table 2. Numerical Data showing transmission efficiency of two-layer Goubau line

Frequency (GHz)	$\mathbf{|S_{11}|}$	$\mathbf{|S_{21}|}$	**Transmission efficiency**
2.94	0.02378	0.868	75.3 %
3.45	0.31662	0.83327	69.5 %
3.5	0.25253	0.85677	73.5 %
3.54	0.19618	0.87504	76.6 %
3.6	0.12222	0.90968	82.8 %
3.98	0.27754	0.85566	73.3 %
4.42	0.08996	0.94635	89.6 %
4.6	0.23448	0.8547	73.1 %
4.64	0.27284	0.82736	68.5 %
4.7	0.3154	0.80848	65.5 %
5	0.16224	0.89556	80.3 %
5.06	0.009	0.907	82.3 %

From Table 2, it can be noticed that the transmission efficiency of the transmission line varies from 73% to 89.6% over the frequency ranging from 3.5 GHz to 4.6 GHz. Hence the proposed planar Goubau line has a bandwidth of 1.1 GHz with transmission efficiency of above 73% and achieving a maximum transmission efficiency of 89.6% at 4.42 GHz, which is an improvement over the single-layer PGL model.

Based on the simulation results in CEMS, the following observations made :

1. Adding the dielectric layer on top of the single-layer PGL improves the overall transmission efficiency and results in a bandwidth equal to 1.1 GHz.
2. S_{21} can be increased by
    i. Adding a dielectric substrate on top of the metal layer
    ii. Increasing the dielectric constant
    iii. Improving the tapering of the metal line
3. S_{11} can be reduced by
    i. Improving the CPW transition
    ii. Extending the CPW
4. Increasing the length of ground plane results in the resonance frequency being shifted towards higher frequency.

5.2 GOUBAU-LINE-BASED ANTENNA SIMULATION IN CEMS

The proposed antenna design is simulated in CEMS over the frequency range of 0.2 GHz to 5 GHz, and the corresponding frequency response of S parameter is shown is Figure 17. It can be noticed that the antenna achieves a good input impedence matching of -16 dB at the frequency of 3 GHz.

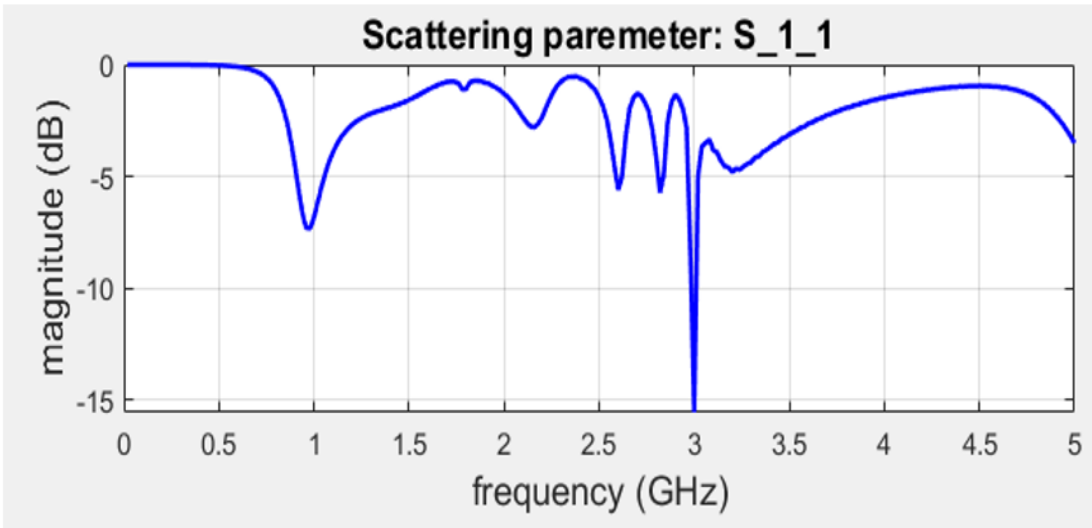
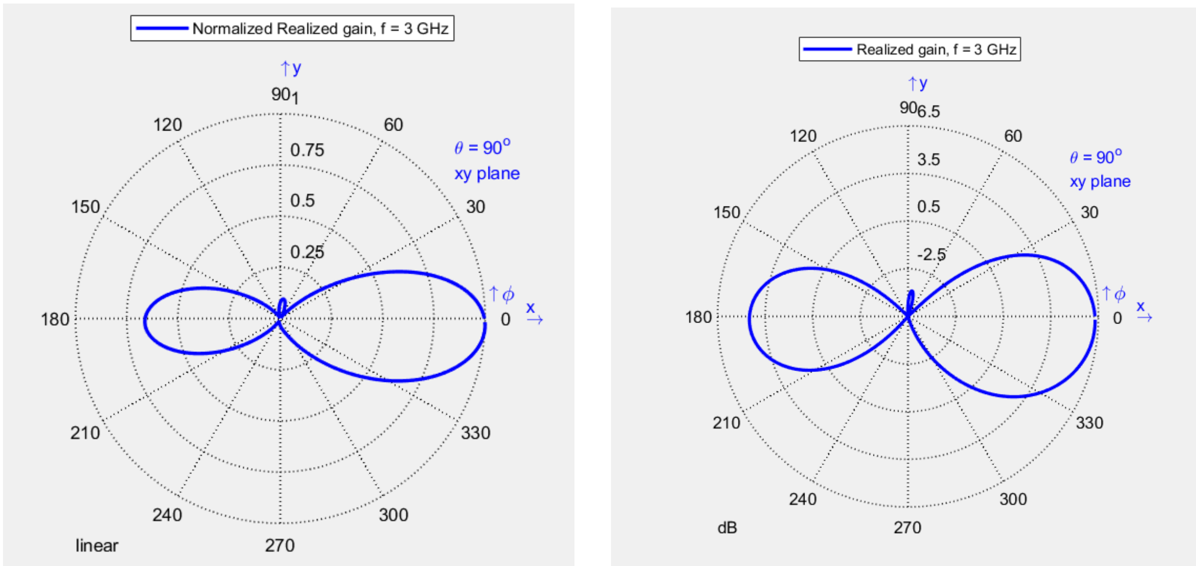


Figure 17. Frequency response of proposed leaky antenna.

Next the farfield of the antenna is simulated at the resonant frequency of 3 GHz and the corresponding radiation pattern obtained is as shown in Figure 18. It can be noticed that the proposed leaky wave antenna radiates strongly in the forward direction at a frequency of 3GHz with maximum realized gain of 6.5 dBi and a radiation efficiency of 93%, where radiation efficiency obtained from CEMS is the ratio of total power radiated to the total power transmitted.

From the Figure 18, it can be observed that, while this Goubau-line-based antenna design succeeds in obtaining a strong directive pattern in the forward direction, the design fails at suppressing a significant backward radiation, which is around 4 dBi. Here x axis is the forward direction based on the antenna alignment in CEMS.



(a) (b)

Figure 18. Radiation pattern in xy plane showing the realized gain (a) linear scale (b) dB scale.

Following are the observations made based on the parametric study of the antenna design shown in Figure 12:

1) Position of the first stub (*p*)

   As the distance between the first stub and the CPW transition increases, S_{11} is improved. But in order to reduce the length of the antenna, the first stub was moved closer to CPW so that the value of S_{11} was adjusted to -16 dB.

2) Distance between stubs (*d)*

   Distance between stubs decides the maximum gain and whether the beam is directive or not and whether it is forward directed or backward directed.

3) Length of the stub (*l*)

   Increasing the length of the stub has shown a decrease in radiation frequency and vice versa.

4) Width of the stub (*w*)

   Increasing the width of the stub has shown a slight increase in gain, but further increasing the width makes the pattern less directive.

5) Length of CPW (*c*)

   Reducing the length of CPW increases the return loss (S_{11}), but in order to bring down the antenna size the length of CPW was reduced so that the value of S_{11} was reduced to -16 dB.

CHAPTER 6

CONCLUSIONS

The proposed planar Goubau line with two-layer dielectric design was simulated in CEMS and promising results were obtained. The design was able to achieve a maximum transmission efficiency of 89.6% at 4.42 GHz and has a transmission efficiency of above 73% over the frequency range of 3.5 GHz to 4.6 GHz, which is an improvement over the single-layer PGL.

The proposed Goubau-line-based antenna was designed and simulated at a frequency of 3 GHz, radiating with a forward gain of 6.5 dBi, and has a radiation efficiency of 93%. Even though this antenna design shows the possibility of obtaining a directive radiation pattern in the forward direction with reduced antenna size of $0.75\lambda_c$, the design fails at suppressing the significant backward radiation, which is around 4 dBi.

6.1 FUTURE RESEARCH

The proposed antenna design could be used in combination with a photoswitching circuit to steer the main beam. Adding the beam steering features to an endfire antenna makes it suitable for applications in radar and communication systems. Also, further modification of the design to suppress the radiation in backward direction along with reducing the overall size could be studied.

REFERENCES

[1] G. Goubau, "Surface waves and their application to transmission lines," *J. Appl. Phys.*, vol. 21, no. 11, pp. 1119–1128, 1950.

[2] G. Goubau, "Designing Surface waves," *Electronics Journal, April 1954.*

[3] U.S. Patent 2,921,277*, "Launching and receiving of surface waves."* George J. E. Goubau.

[4] U.S. Patent 2,685,068, *"Surface wave transmission line."* George J. E. Goubau.

[5] Tahsin Akalin, Anthony Treizebre, and Bertrand Bocquet, "Single-wire transmission lines at Terahertz frequencies*," IEEE Transactions on Microwave Theory and Techniques,* vol. 54, no. 6, pp. 2762-2767, June 2006.

[6] Jordan S. Besnoff and Matthew S. Reynolds, "Single-wire radio frequency transmission lines in biological tissue," *Applied Physics Letters 106*, 183705 (2015).

[7] J. Musson et al., "*Application of Goubau Surface Wave Transmission Line for improved Bench Testing of Diagnostic Beamline elements*," Proc. of PAC09, 2009.

[8] A. Oral Salman, D. Dibekci, Sergey P. Gavrilov, and Alexey A. Vertiy, "The radiation properties of a novel wire antenna for the security fence radar," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 9, September 2008.

[9] Jiro Chiba, "Experimental studies of the losses and radiations due to bends in the Goubau line," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-25, no. 2, pp. 94-100 February 1977.

[10] A. Treizebre, S. Laurette, Y. Xu, R. G. Bosisio and B. Bocquet, "THz Power Divider Circuits on Planar Goubau lines (PGLs)," *Progress in Electromagnetics Research C"*, Vol. 26, 219–228, 2012.

[11] D. Sanchez-Escuderos, M. Ferrando-Bataller, J. I.Herranz, and M. Cabedo-Fabres, "Periodic Leaky-wave Antenna on Planar Goubau Line at Millimeter-wave Frequencies," *IEEE Antennas Wireless Propagation Letters*, 12, August 2013, pp. 1006–1009, doi:10.1109/LAWP.2013.2278035.

[12] X.-L. Tang *et al.*, "Continuous beam steering through broadside using asymmetrically modulated Goubau line leaky-wave antennas," *Sci. Rep.*, vol. 7, Sep. 2017, Art. no. 11685.

[13] Qingfeng Zhang, Xiao-Lan Tang, Sanming Hu and Yifan Chen, "A reconfigurable Goubau line based leaky wave antenna," *2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018.*

[14] Karthik Rudramuni, Krishnamoorthy Kandasamy, Qingfeng Zhang, Xiao-Lan Tang, Abhishek Kandwal, Puneeth Kumar Tharehalli, Rajanna and Haiwen Liu, "Goubau-line leaky-wave antenna for wide-angle beam scanning from backfire to endfire," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 8, pp. 1571-1574 August 2018.

[15] Ge Zhang, Qingfeng Zhang, Yifan Chen, Senior Member and Ross D. Murch, "High-Scanning-Rate and Wide-Angle Leaky-Wave Antennas Based on Glide-Symmetry Goubau Line," *IEEE Transaction on Antennas and Propagation*, 2019, DOI 10.1109/TAP.2019.2951524.

[16] Karthik Rudramuni, Puneeth Kumar Tharehalli, Krishnamoorthy Kandasamy, Basudev Majumder and Qingfeng Zhang, "Goubau-line based endfire antenna," *Int J RF Microw Comput Aided Eng.* September 2019, pp. 1-7, e22008.

[17] "AppCAD Design Assistant," *Broadcom Inc.* [Online]. Available: https://www.broadcom.com/appcad.