FEKO Student Competition 2017

Design of a Two Port Dual-Polarized Trefoil Torus Knot Antenna using Characteristic Mode Analysis

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Motivation and Objectives

Challenge

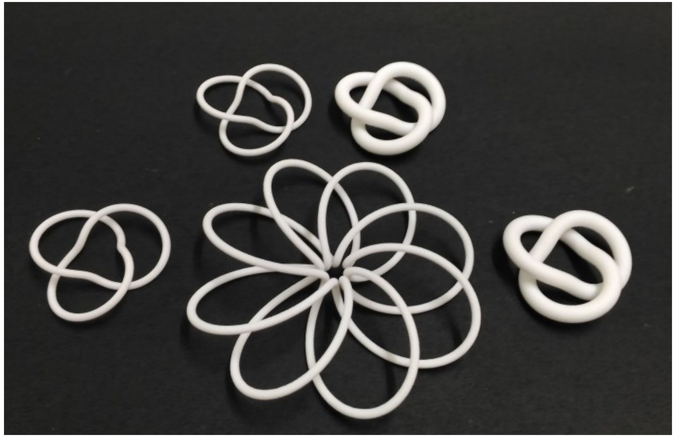
Rapid development in communication technologies is motivating the antenna designers to use the available 3D Space efficiently. 3D curves such as "Knots" find interesting applications in various fields of electromagnetics. Due to their inherent symmetry, they give rise to orthogonal degenerate radiating modes. Major challenge is to identify and excite these modes. Characteristic Mode Analysis (CMA) of FEKO is used to realize the novel knot antenna.

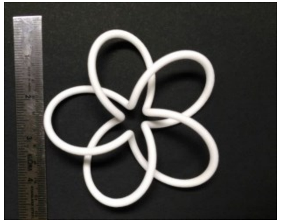
Objectives

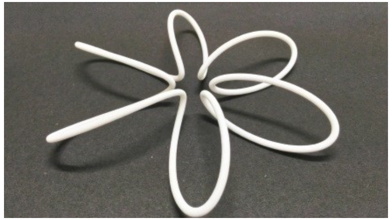
a) To study the radiation properties of trefoil knot using characteristic mode analysis
b) To examine the suitable excitation method
c) To realize dual-mode polarization diversity antenna using a knot
d) To fabricate the prototype, measure the results in an anechoic chamber and compare with the simulated results

Features Used

Standard Configuration, Multiport S-Parameter, Characteristic Mode Analysis (including modal weighting and excitation coefficient)







Few knotted structures realized in our lab
(Real photo not rendered image)

Trefoil Torus Knot Construction

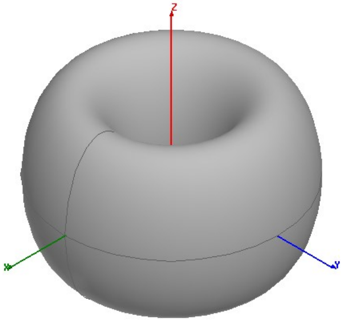


Fig. 1(a)

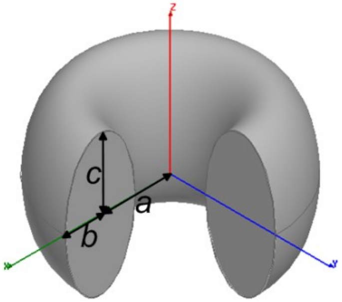


Fig. 1(b)

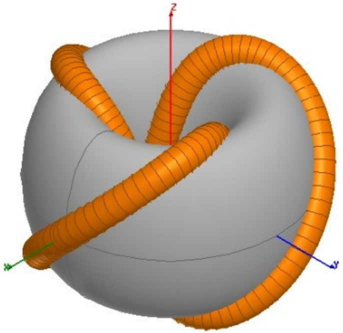


Fig. 1(c)

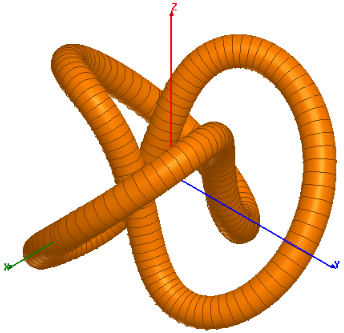


Fig. 1(d)

Evolution of Trefoil Torus Knot

Fig. 1(a) shows an elliptical torus and Fig. 1(b) shows a portion of the torus with major radius *a* and minor radii *b* and *c*, respectively. A trefoil knot is wrapped around the torus as shown in Fig. 1(c). The final trefoil knot geometry alone is shown in Fig. 1(d). Parametric equations describing the trefoil torus knot can be written as mentioned in [1] and [2].

Parametric Equation

$$x = (a + b\cos(\psi + qs))\cos(ps)$$

$$y = (a + b\cos(\psi + qs))\sin(ps)$$

$$z = c\sin(\psi + qs)$$

Where $p = 2$, $q = 3$, ψ and S varies from 0 to 2π.

[1] S. V. Kumar and A. R. Harish, "Trefoil Torus Knot Monopole Antenna," in *IEEE Antennas and Wireless Propag. Lett.*, vol. 15, pp. 464-467, 2016.
[2]D. H. Werner, D. M. Jones, and P. L. Werner, “The electromagnetic fields of elliptical torus knots,” IEEE Trans. Antennas Propag., vol. 49, pp. 980–991, Jun. 2001.

Characteristic Mode Analysis

Motivation

To gain a physical insight into the radiation properties of a trefoil knot, In the following section CMA for the proposed trefoil knot is performed and its results are discussed. Fig. 2(a), (b) and (c) shows the different view of actual trefoil knot constructed in CADFEKO using the analytical curve option. Thin wire geometry is chosen for easier simulation.

Knot Geometry	
Parameter	Value in mm
a	9.29
b	6.62
c	4.13
t	0.2
t: Wire diameter	

Please to refer Fig. 1 for the a description of the symbols

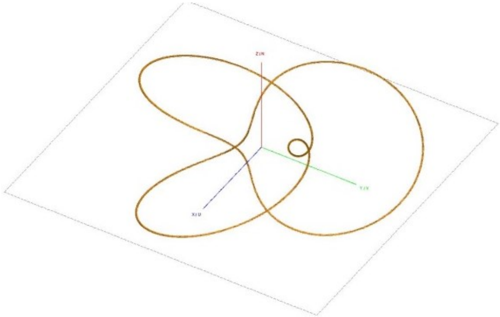


Fig. 2(a) Isometric view

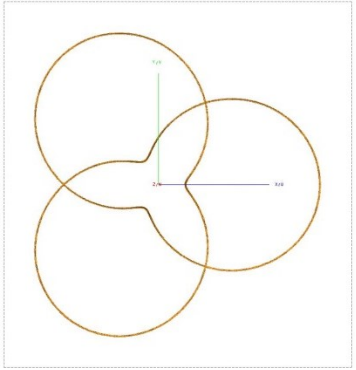


Fig. 2(a) Top View

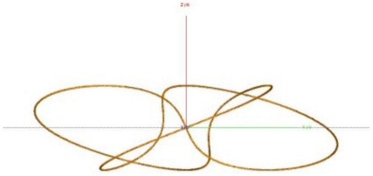


Fig. 2(a) Side View

Trefoil Geometry for CMA

Characteristic Mode Analysis

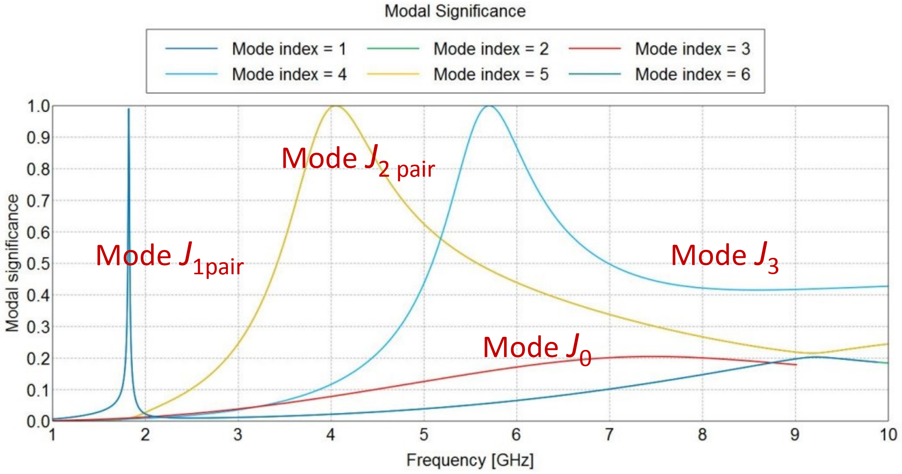


Fig. 3(a) Obtained Modal Significance

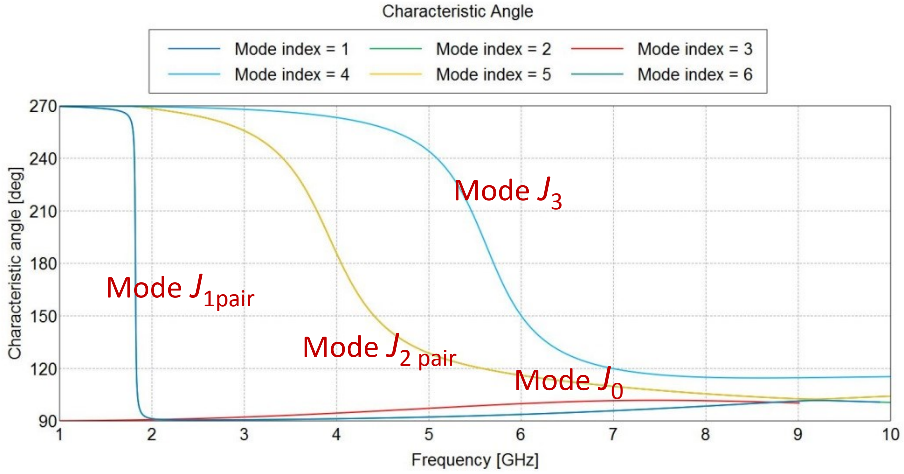


Fig. 3(b) Obtained Characteristic Angle

Modal Significance and characteristic angle

The modal significance and characteristic angle of trefoil knot radiating in free space are shown in the Fig. 3(a) and (b), respectively. Results are generated using macro CMA-Plotter*. Mode index 3 is a non radiating mode and named as Mode J_0. Modes with indices 1 and 2 form the first degenerate mode pair and are named collectively as Mode J_1 pair. Next degenerate mode pair is named as Mode J_2 . The Last mode is Mode J_3.

*https://www.feko.info/support/lua-scripts/cma-plotter/CMA-plotter

Mode Characteristics

Mode	Resonant Frequency [GHZ]	Total length of the knot (λ)
Mode J_0	- -	
Mode J_1	1.804	0.97
Mode J_2	4.294	2.17
Mode J_3	5.830	3.05

Characteristic Mode Analysis Contd..

Mode J_0

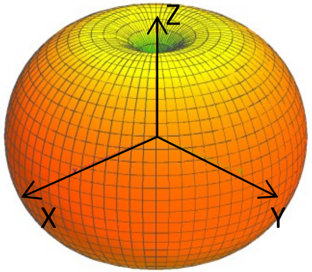


Fig. 4(a)

Mode J_0

Shown in Fig.4 (a). It is non radiating mode as the modal significance is very small compared to 1. Pattern is omnidirectional and having null in broadside direction. Polarization is horizontal.

Mode J_1 Pair

Shown in Fig.4 (b). Arises due to the rotational symmetry similar to thin wire closed loop. Pattern is omnidirectional with Mode J_1 having a null oriented along the X-axis and Mode J_1' having null along the Y-axis. Since the bandwidth is low (observed from modal significance in Fig.3 (a)) excitation of this mode is difficult.

Mode J_1 | Mode J_1'

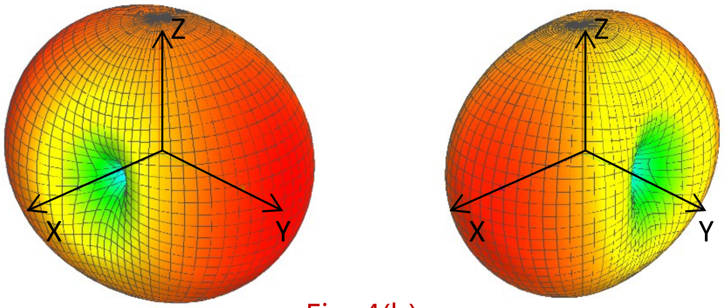


Fig. 4(b)

Characteristic Mode Analysis Contd..

Mode J_2	Mode J_2'

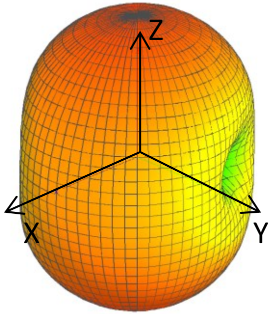
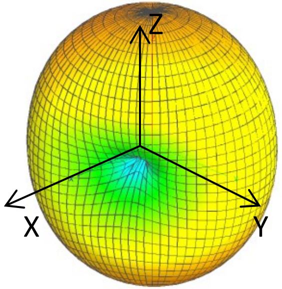


Fig. 4(c)



Mode J_2 Pair

Illustrated in Fig. 4(C). This mode arises due to three -fold rotational symmetry of trefoil torus knot. The maximum is along the Z-axis and hence can be used to realize a broadside radiating antenna. The bandwidth of this mode pair is wide and can be controlled by adjusting the ratio of a to (b/c). Mode J_2 pair is the desired mode in this work. The idea is excite the degenerate orthogonal Mode J_2 pair. This is realized by strategically placing two probes to excite this mode and optimizing the dimensions.

Mode J_3

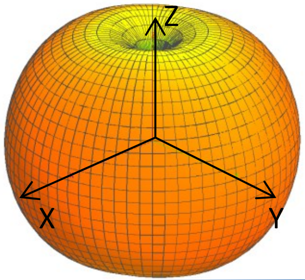


Fig. 4(d)

Mode J_3

Another mode having omnidirectional an radiation pattern shown in Fig. 4(d). The interesting feature is the elliptical polarization is in the direction of maximum radiation, which can be optimized to realize an omnidirectional antenna with circular polarization [3] and [4].

[3] S. V. Kumar and A. R. Harish, "Generation of Circularly Polarized Conical Beam Pattern Using Torus Knot Antenna," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 11, pp. 5740-5746, Nov. 2017.
[4]S. V. Kumar and A. R. Harish, "Generation of circularly polarized conical beam pattern using (3, 8) torus knot antenna," *2017 11th European Conference on Antennas and Propagation (EUCAP)*, Paris, 2017, pp. 3449-3451.

Current Distribution Study

Thick wire knot on an infinite ground plane

The knot is constructed from free software called OpensSCAD* and imported using "import mesh" option in CAD FEKO. Fig. 5(a) shows the current distribution of Mode J_2 and its corresponding radiation pattern. It is observed that orientation of current is along the direction of X-axis. The current distribution for Mode J_2' is shown in Fig. 5(b) along with the radiation pattern. The current distribution is predominantly along Y-axis. The radiation is maximum in the broad-side direction for both the modes. By properly exciting these modes a dual-polarized antenna can be realized.

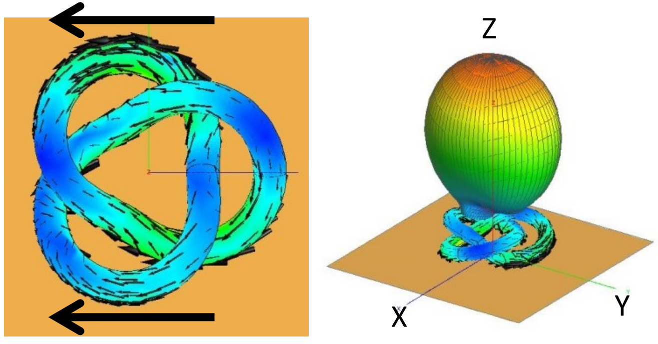


Fig. 5(a) Mode J_2

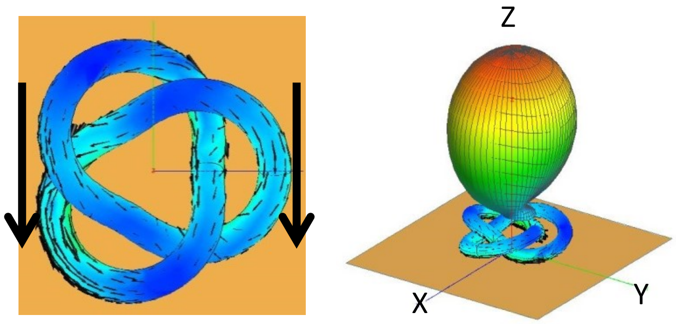


Fig. 5(b) Mode J_2'

* Sample code for constructing trefoil knot in OpenSCAD is presented in slide number 19

Probe Design

Excitation Geometry

To effectively excite Mode J_2 and mode Mode J_2 ', disc loaded monopole probe is used, which is shown in Fig. 6. The height h of monopole and disc radius r can be adjusted optimally to get maximum coupling between probe and knot. The location of probe is chosen by studying the electric current distribution of the trefoil torus knot.

Parameters	
Parameter	Description
r1 h1 d1 r2 h3	Probe_1 Disc Radius Probe_1 Height Distance between probe1 and origin Substrate radius Substrate Height
r2, h2, and d2 are probe_2 parameters with same functionality (including h3 not shown in figure)	

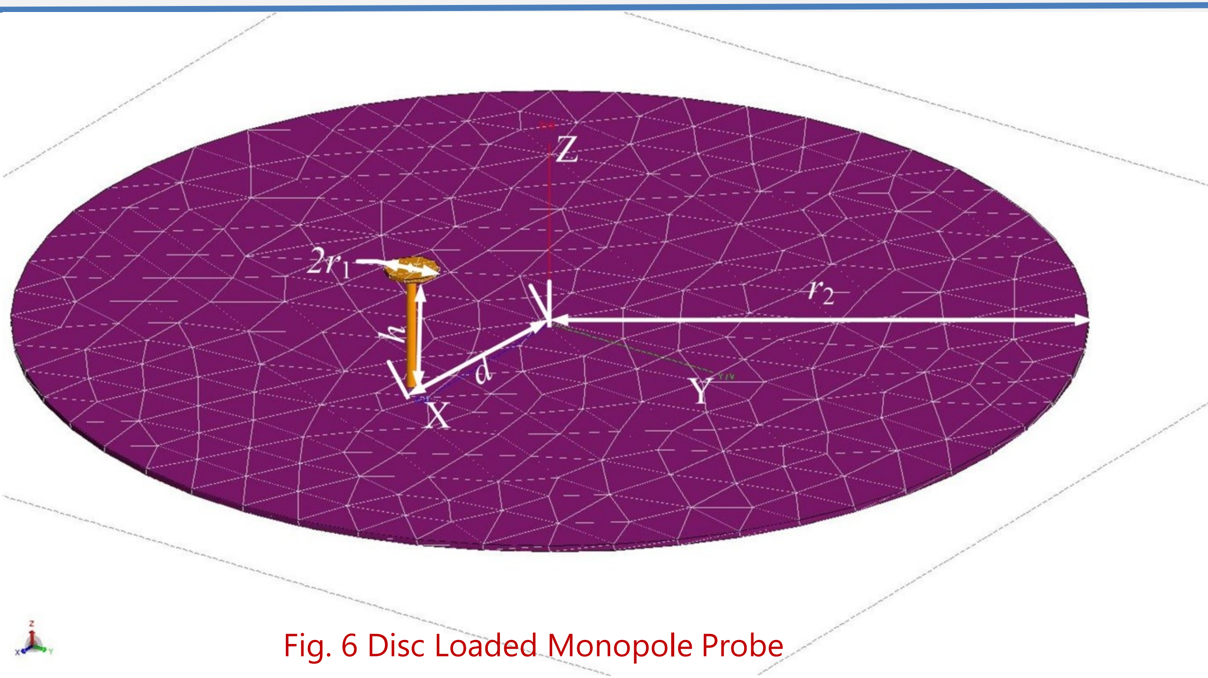


Fig. 6 Disc Loaded Monopole Probe

Antenna configuration

Complete Antenna Geometry

Figure shows the complete antenna geometry. Torus knot constructed using OpenSCAD is placed above the Fr4 Substrate. Bottom side of substrate is ground plane. Two disc loaded monopole are placed strategically to excite Mode J_2 pair. Multiport s-parameter simulation is done to get the complete s-matrix and standard configuration simulation is performed to obtain the radiation pattern for each port. Dimension details are tabulated in next slide.

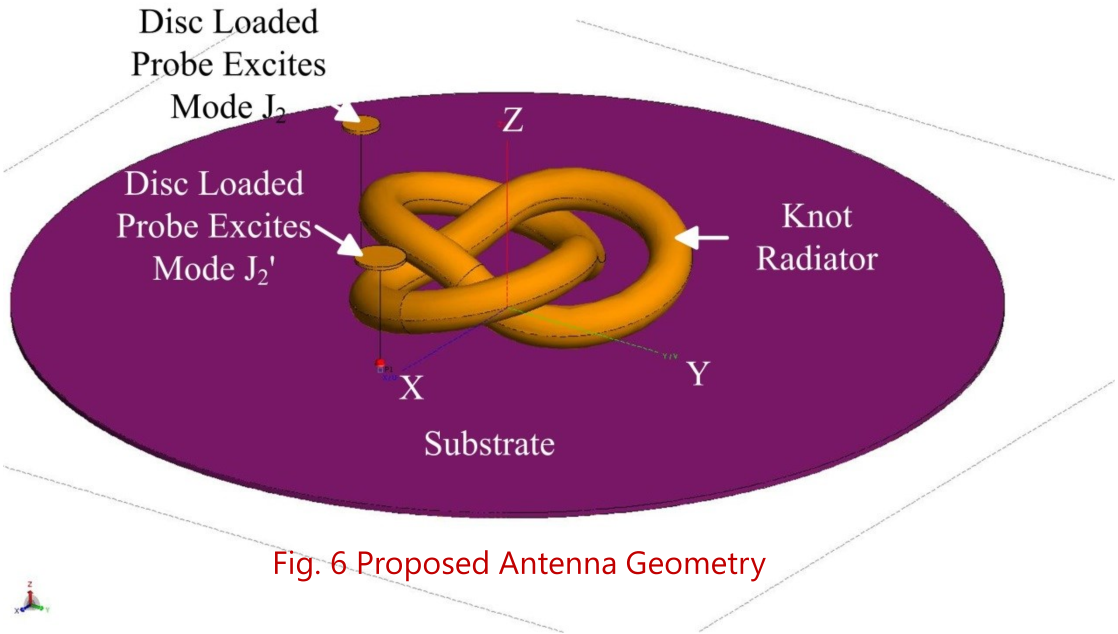


Fig. 6 Proposed Antenna Geometry

Antenna configuration contd..

Parameters	
Parameter	Values in mm
a	16.4
b	6.62
c	4.1
t	6.06
r1	3.66
h1	17.16
Probe1 Position	(27.185,-2.857)
r2	2.66
h2	19.7
Probe2 Position	(-5.7, -26.87)
r3	70
h3	0.8
The table shows the optimized dimensions of proposed antenna geometry	

Multiport S- Parameter results

Scattering Matrix

The optimized scattering matrix obtained from Multiport S-Parameter simulation is shown in the Fig. 7. It can be observed that the reflection coefficient is optimized for better performance at 2.4 GHz. The isolation between the two ports is more than 20 dB at the 2.4 GHz. The operating frequency range is from 2.35 GHz to 2.46 GHz.

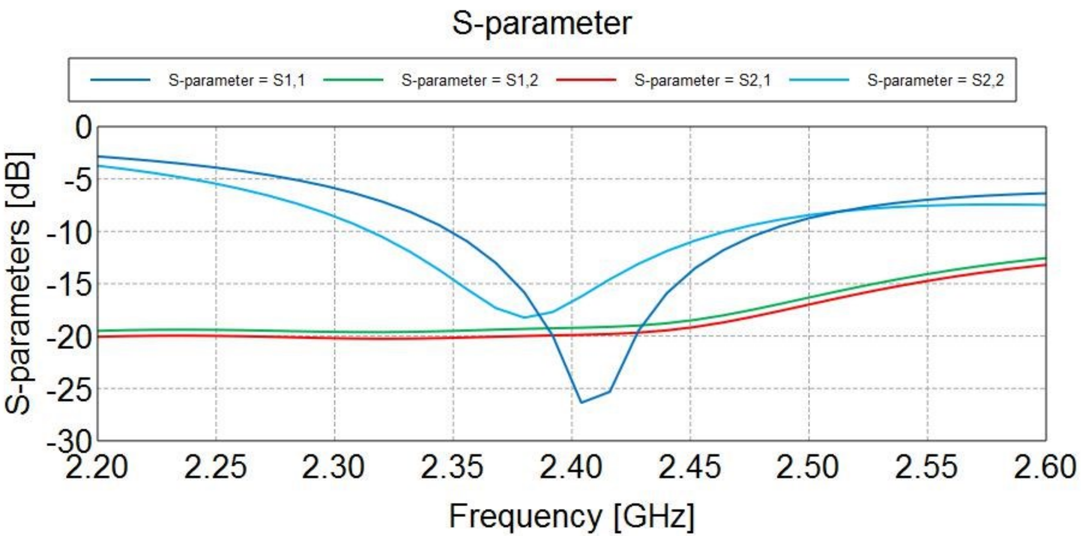


Fig. 7 Simulated Scattering Matrix

S-parameters Magnitude - Two port cma final

Standard Configuration Results

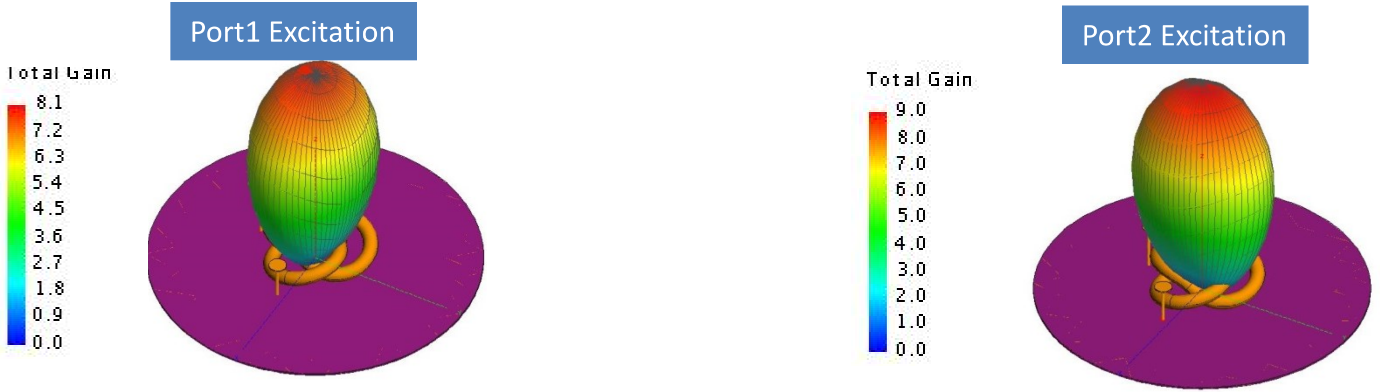


Fig. 7 Obtained 3D Radiation Pattern of the Knot Antenna at 2.4 GHz.

Radiation Pattern

Standard configuration option is used to obtain the radiation performance of the proposed knot antenna. The simulated radiation pattern at 2.4 GHz for the both ports are presented in above Fig.7. The obtained co-polarized gain for both port excitations at 2.4 GHz is above 8 dBi. Results are later compared with the measured radiation performance in anechoic chamber.

Verification of Mode Excitation

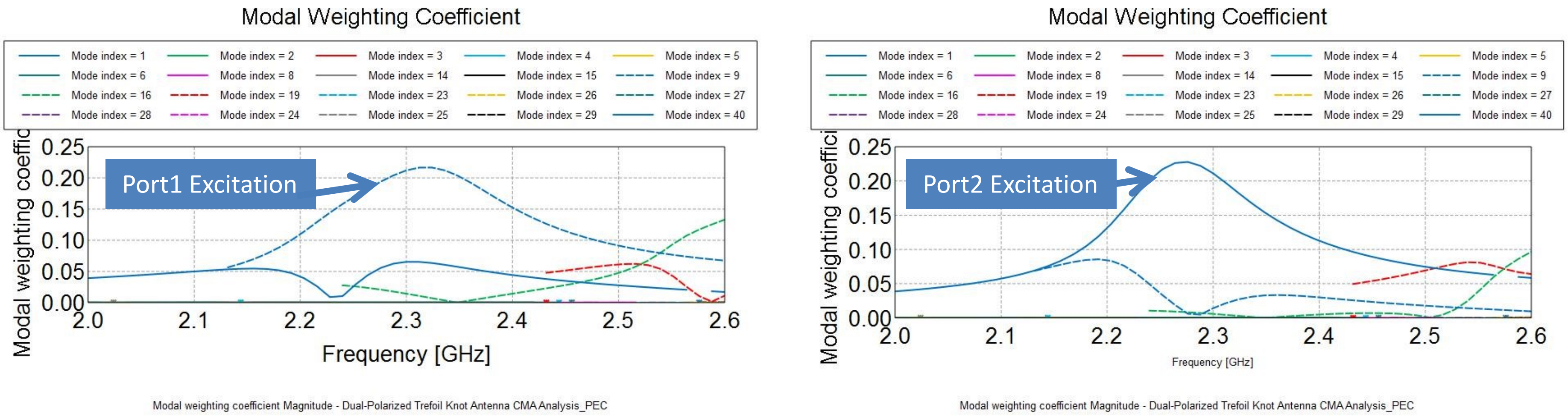


Fig. 8 Modal Weighting Coefficient of Both Ports Over the Range of Frequency.

Modal Weighting Coefficient

The effect of feeding structure on modes can be understood by using modal weighting coefficient feature. CMA analysis for the antenna geometry is performed by replacing ground plane with infinite perfect electric conductor. The first figure shows the modal weighting coefficient calculated at different frequencies for different modes. It can be observed that Port 1 excites the Mode J_2' mode efficiently. Similarly the next figure illustrates the modal weighting coefficient for Port 2 excitation. Evidently the results show that Mode J_2 is getting excited. Thus one can conclude that the proposed disc loaded feed setup excites the knotted radiator efficiently.

Fabrication of proposed knot antenna

3D Printing

The proposed antenna is fabricated using 3D printing technology called selective laser sintering. The obtained prototype is then coated with copper by electroless plating. About 60 microns of copper layer are deposited over the surface of the 3D printed prototype. Conformal coating is applied above the plated knot to prevent oxidation. Once the knot is metalized, it is mounted above the grounded substrate. The disc loaded monopole probes are added using SMA connectors at the bottom of the substrate. Finally its reflection coefficient characteristics are measured using VNA and radiation patterns are measured in an anechoic chamber.

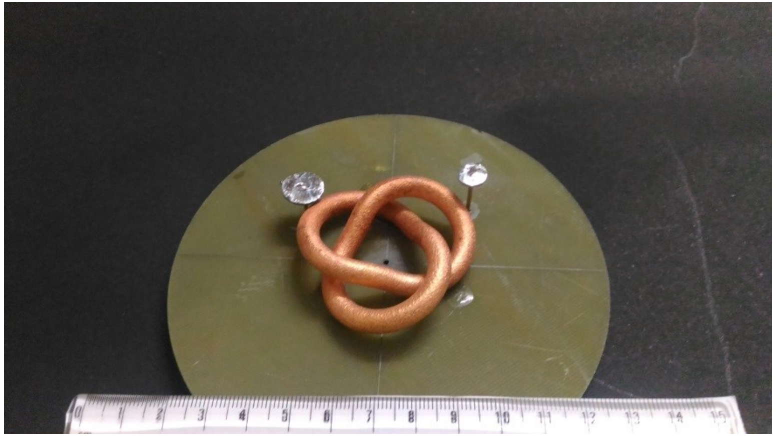


Fig.9 Fabricated Knot antenna

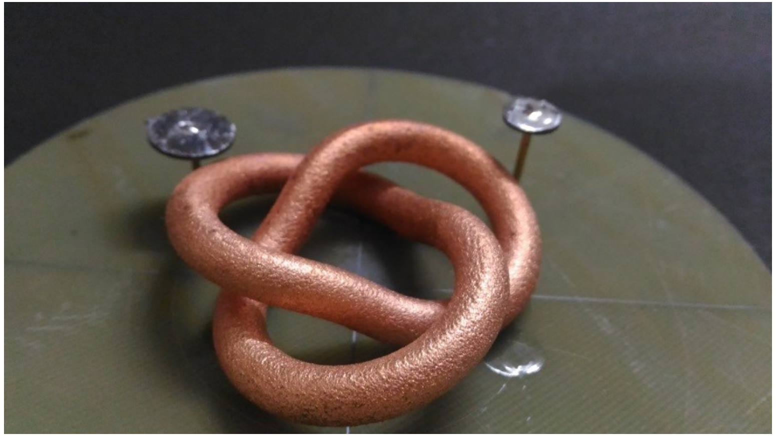


Fig.10 Close-up View

Measured S Matrix

Scattering Matrix Measured

Fabricated prototype is characterized using the vector network analyzer. Slight tuning of probe height and disc radius is done to get better performance. Measured scattering matrix is presented in the Fig. 10. It can be observed that both Port1 and Port 2 has better reflection coefficient at 2.4 GHz. There is reduction in isolation in lower frequency range, However it is not affecting the frequency of interest.

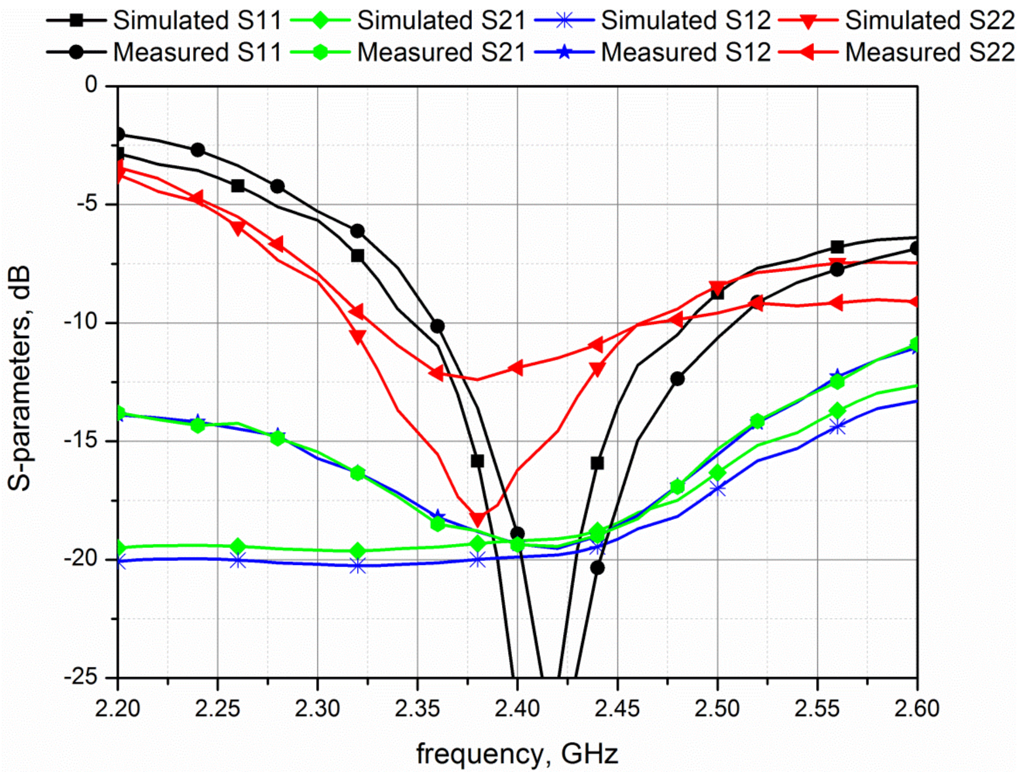


Fig. 10 Measured scattering matrix in comparison with simulated scattering parameters

Radiation Pattern

Port1 Excitation

Port2 Excitation

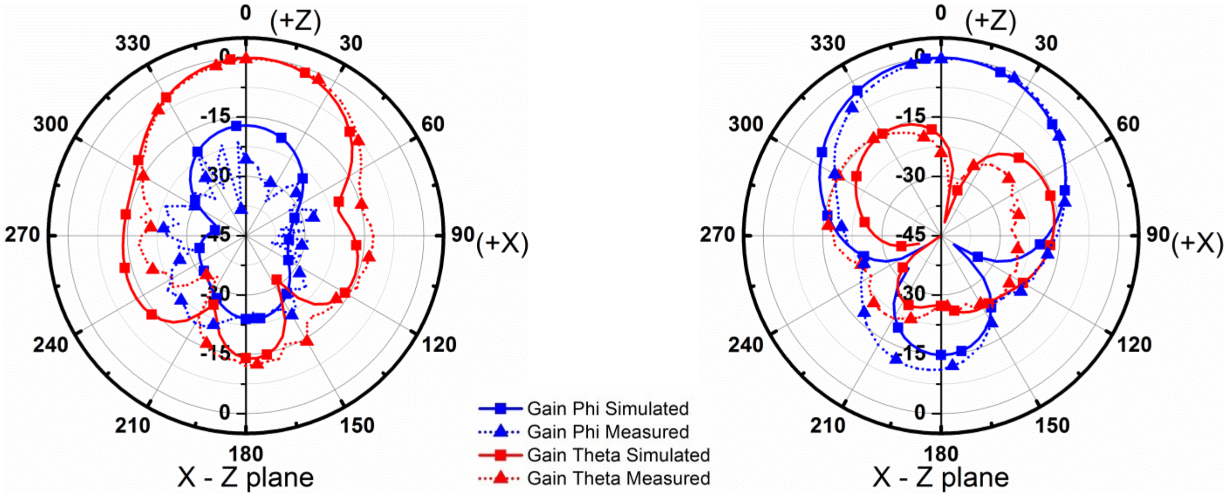


Fig. 11 Measured and Simulated Radiation Pattern at 2.4 GHz in XZ Plane.

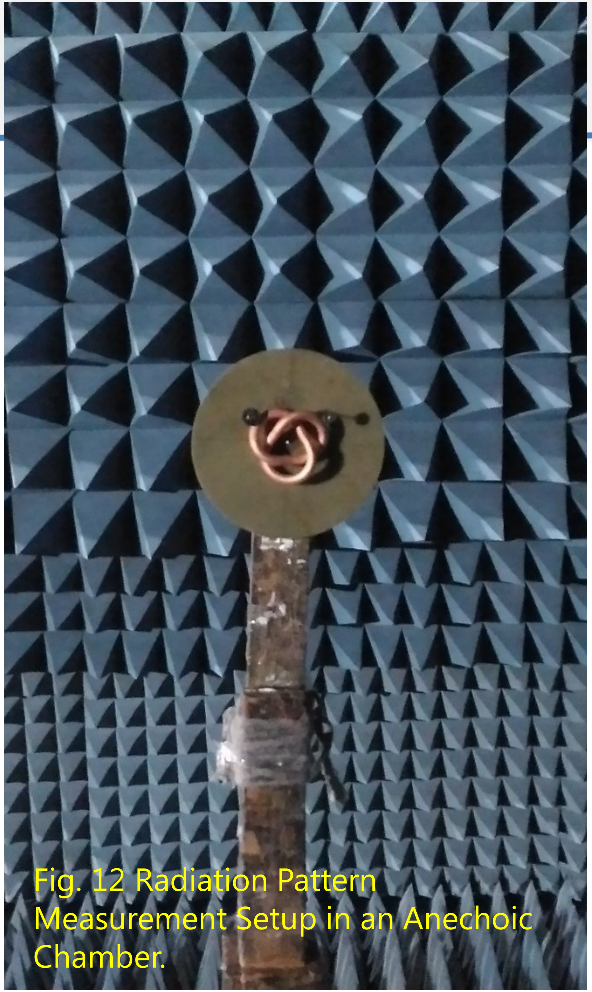


Fig. 12 Radiation Pattern Measurement Setup in an Anechoic Chamber.

Radiation Pattern

The radiation pattern for the fabricated prototype is measured in an anechoic chamber. Fig. 11 shows comparison of measured and simulated results at 2.4 GHz at XZ Plane, one can observe that there is reasonable match between measured and simulated results.

Appendix

Sample Openscad program to draw trefoil knot

```
//sample program to draw parametric knot in OpenSCAD for reference only
// should be modified and scaled according to  the requirement
a=10; //Major radius of Virtual Torus
b=5;//Minor radius of Virtual Torus
c=4;//Minor radius
p=2;
q=3;
//Define analytical curve path for sweeping
function trefoil(s) =
 [ (a+(b*cos(q*s)))*cos(2*s),
   (a+(b*cos(q*s)))*sin(2*s),
   c*(sin(q*s))
 ];
Sweep_Sphere(1,0, 3, 360);
module Sweep_Sphere(r, initial, step, final) {
 for (s=[0: step: final+step]) {
  hull() {
   translate(trefoil(s)) sphere(r);
   translate(trefoil(s+step)) sphere(r);
       }
   }
};
```

Conclusion

Summary and Conclusion

A novel two port dual polarized knot antenna is presented in this work. The radiating structure is systematically studied using characteristic mode analysis feature in FEKO. Orthogonal degenerate Mode J_2 pair is chosen for realizing the antenna. Current distribution of the same mode is studied using FEKO. Disc loaded monopole is chosen for excitation. Multi port s- parameter is utilized to optimize the performance of the antenna at desired frequency. Standard configuration setup of FEKO is used for studying the radiation pattern. Modal weighting coefficient results by FEKO is investigated to ensure that the desired mode is getting excited. Antenna geometry is fabricated using 3D printing technology. Realized antenna performances are measured and compared with the simulated results.