Design and Analysis of Microstrip Patch Antenna Operating at Higher Order Mode

Muhammad Adil Khan[1], Shahid Bashir[1], Awais Khan[2*], Muhammad Awais[1]
[1]Department of Electrical Engineering, University of Engineering & Technology, Peshawar
[2]Department of Electrical Engineering, University of Science & Technology, Bannu, Pakistan
[*]**Correspondence:** engr_awais@yahoo.com

Citation | Khan. M. A, Bashir. S, Khan. A, Awais. M, "Design and Analysis of Microstrip Patch Antenna Operating at Higher Order Mode", IJIST, Vol. 6 Issue. 3 pp 1099-1109, Aug 2024

Received | June 22, 2024 **Revised |** Aug 18, 2024 **Accepted |** Aug 19, 2024 **Published |** Aug 21, 2024.

This paper proposes an enhanced bandwidth microstrip patch antenna by exciting it with higher order modes. Characteristics Mode Analysis (CMA) is used to analyze and understand the possible modes for bandwidth enhancement of microstrip patch antenna. Furthermore, Defected Ground Structure (DGS) technique is utilized for bandwidth enhancement. The proposed antenna is having a size of 67.5 × 67.5 mm^2 with an operating frequency of 5.8 GHz. The impedance bandwidth is increased by 13.8% using Defected Ground Structure (DGS) by adding slots in the ground for higher order mode operation. Moreover, the proposed antenna has an overall efficiency of above 80. Therefore, enhanced impedance bandwidth, improved radiation pattern, and compatible design make the design novel and suitable for practical wireless applications.

Keywords: Characteristics Mode Analysis (CMA), Higher Order Mode (HOM), Bandwidth Enhancement, Patch Antenna.

Introduction:

Owing to multiple advantages such as light weight, low cost and easy fabrication, most of the researchers prefer to use microstrip patch antennas. However, microstrip patch also have certain limitations such as low gain, limited bandwidth and low radiation efficiency. The simultaneous increase of the bandwidth and gain is a challenging issue over the past years. Several techniques have been used to improve the bandwidth of microstrip patch antenna. These techniques include use of slot radiators [1][2][3][4], slotted patch [5][6][7][8], thick substrate [9][10][11], different geometries [12][13], various feeding techniques [14][15] and Defected Ground Structure [16][17][18] for bandwidth enhancement. In [19] substrate integrated waveguide has been used to improve the gain and bandwidth simultaneously but it makes design more complex, and size of antenna is also increased. In [20] real time beam scanning has been achieved in concentric circular antenna using higher order mode. In [21] relative parameter of substrate has been parametrically varied in order to have a high gain in circular patch antenna with higher order mode of TM12. Enhancing the thickness of substrate and decreasing the permittivity of substrate we can get the expanded bandwidth, which is simple method, but it reduces the quality factor Q. In [22] radiating patch of Wang-shaped is used to increase the bandwidth by up to 49.3% having profile of $0.2\lambda_0$. In [3], an inverted U -shaped slot is etched on the patch antenna to increase the bandwidth up to 17.8% having thickness of $0.09\ \lambda_0$. In [6] patch antenna with E shaped is used to increase the bandwidth to 30.3% having profile 0.1% $\lambda_{0.}$ Furthermore, in [23] using both TM10 and TM30 mode, the bandwidth has been increased to 8%. The gain of antenna has been improved using higher order modes that is TM70 by reducing the side lobe levels in [24] using star shape patch antenna. In [25] DGS techniques are used by etching H-shape slot in the ground for enhancing bandwidth of the patch antenna. Furthermore, [25] also uses DGS technique by using complementary rectangular slot in patch antenna for improving bandwidth of patch antenna. In [26], surface modification and stub loaded technique has been used in order to excite higher order modes for bandwidth enhancement. In [27] a wide rectangular slot antenna operating under TM03 mode is reported. In [28] in order to reduce side lobes levels of TM03 mode, narrow slots techniques were introduced at the rectangular patches for the improvement of adjustable beam width and gain. In [29] high gain and low side lobe level can be obtained by simultaneous excitation of both resonate mode i.e. TM11 and TM13 mode. The superposition of far field of both modes made it position for resonating mode simultaneously. In [30] wideband differentially feed patch antenna has been proposed for stable radiation gain using two modes i.e. TM31 and TM12 mode. Moreover, four shorting pins are used in order increase bandwidth by 12.5%. In [31] circular interference and differential feeding techniques has been adopted in order to attain desirable bandwidth for the patch in TM90 mode. However, this paper proposed higher order modes i.e. TM03 with Defected Ground structure in order to increase bandwidth.

Novelty Statement:

This paper presents a novel higher order mode patch antenna with improved bandwidth and enhanced gain using meander lines in the top radiating patch and defected ground structure (DGS) in the bottom ground plane. The compact design of proposed antenna makes it a compatible and suitable for practical wireless applications.

Objective:

Patch antennas operating at lower order mode typically exhibit drawbacks, including poor gain and narrow bandwidth, which are inversely related and therefore difficult to improve simultaneously. However, patch antennas being resonant structures can also operate at higher order modes (HOMs) when properly excited. Therefore, HOMs can be utilized to improve overall antenna performance since they are able to mitigate low bandwidth and low gain when excited properly. This paper presents a novel higher-order mode patch antenna measuring 67.5 mm × 67.5 mm, operating at 5.8 GHz. The antenna's gain and bandwidth are enhanced through the integration of a meander line in the top layer and a Defected Ground Structure (DGS) in the bottom layer.

Research Methodology:

The methodology of the proposed antenna is shown in Figure 1 in the form of flowchart. It started with a detailed literature study of the higher order modes and their analysis, defected ground structures and their impacts on patch antenna performances. CST simulation software was used for the design and simulation of proposed antenna. Various designs were simulated and results were analyzed. After different parametric analysis and optimization process, the final design was proposed showing improved bandwidth and gain performance in comparison with similar works in literature

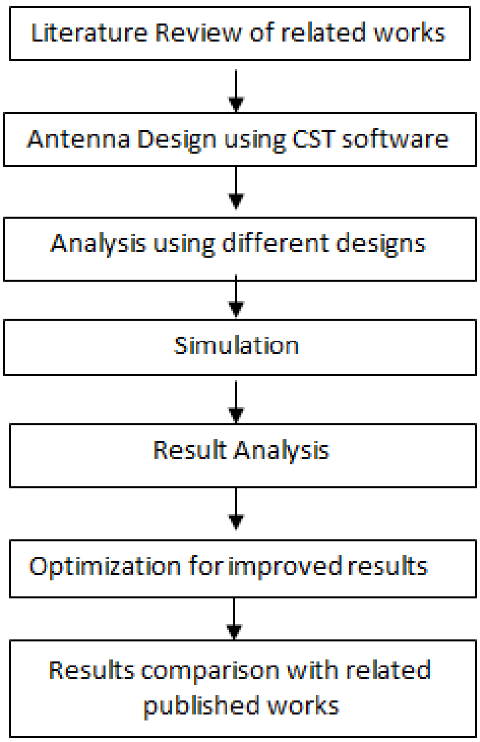

Figure 1: Methodology flowchart

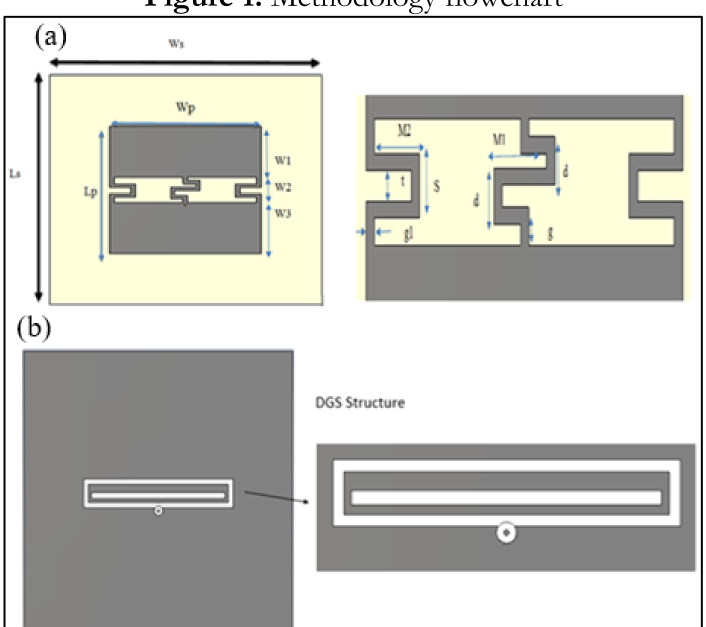

Figure 2: Proposed antenna design (a) front and (b) back view

Antenna Design:

As shown in Figure 2, the proposed Antenna structure is designed using Arlon AD 250 substrate with permittivity (εr = 2.5) and thickness of 1.6mm. The overall size of Antenna is 67.5 × 67.5 mm (Ls × Ws) and the size of the radiating patch turns out to be 37.5 × 37.5 mm2 (Lp × Wp). The patch antenna is connected using mender lines in between two patches to generate higher order modes. The mender line also helps in providing the continuity of current between the lower and upper part of the patch.

Evolution of Antenna:

The proposed antenna is designed step by step as shown in Figure 3. In Figure 3(a) the top view of Ant 1 incorporating meander lines is given. In Figure 3(b) Ant 1 back view without DGS is shown. Figure 3(c) shows Ant 2 back view with H-shaped DGS. Figure 3(d) shows the proposed Ant 3 back view with rectangular shaped DGS.

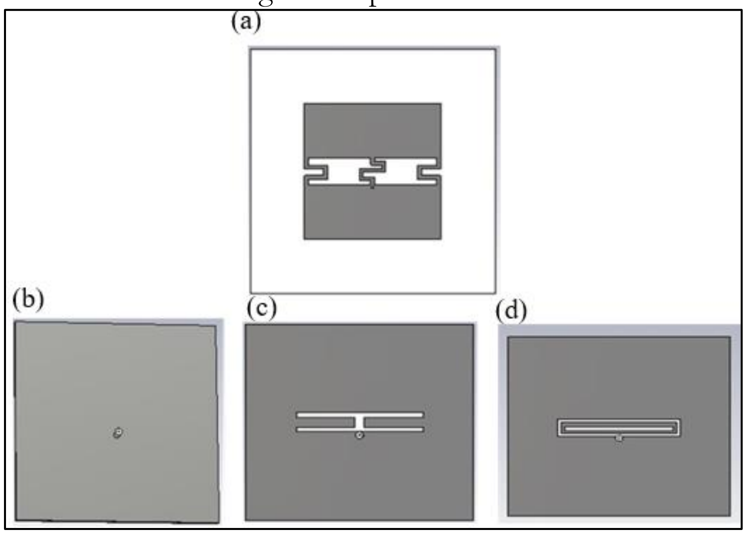

Figure 3: Step by step evaluation of proposed antenna (a) Ant 1 top view (b) Ant 1 back view (c) Ant 2 back view (d) Ant 3 back view

After optimization techniques and simulation for best possible results optimized values of proposed antenna has been finalized and in table 1, Optimized parameter of proposed design is listed

Table 1: List of Parameters

Parameters	Dimensions (mm)	Parameter	Dimensions(mm)
Ls	67.5	M1	6.25
Ws	67.5	M2	5.33
Lp	37.5	d	3.125
Wp	37.5	g	1
W1	15	g1	1.125
W2	7.5	t	1.83
W3	15	s	3.83
Ls1	37.50	Ls2	4.50
Ls3	33.50	Sx	1.2
Sx1	1.5		

In order to improve bandwidth of patch antenna DGS techniques is opted in proposed design. In the proposed design complementary rectangular slot is etched at the ground plane to increase the impedance bandwidth of the patch antenna. The slot in the patch antenna provides a shortest path for the flow of the current the results in increasing the operating bandwidth. Moreover, using DGS techniques mainly reduces the gain of the patch antenna. However, this paper aims to increase the impedance bandwidth without affecting the gain of the patch antenna.

In recent studies, various techniques have been employed to enhance the bandwidth and performance of patch antennas. For instance, [22] reports a Wang-shaped radiating patch that increases bandwidth by up to 49.3% with a profile of 0.2λ0. Similarly, [3] demonstrates that an inverted U-shaped slot etched into the patch can boost bandwidth by 17.8%, with a thickness of 0.09λ0. In [6], an E-shaped patch antenna achieves a 30.3% bandwidth increase with a profile of 0.1λ0. Additionally, [23] shows an 8% bandwidth enhancement using TM10 and TM30 modes, narrow slot techniques to reduce side lobes, and improve beam width and gain achieving bandwidth of 4.9% and gain of 14.6dB [28]. In [29] achieves high gain and low side lobe levels by simultaneously exciting TM11 and TM13 modes and thus achieve and bandwidth of 3.6% and gain of 12.8dB, and [30] proposes a wideband differentially-fed patch antenna with TM31 and TM12 modes and four shorting pins to increase bandwidth by 12.5%. However, the proposed antenna design uses meander lines-based DGS and operates at higher order mode results in achieving increased bandwidth of 13.8% and gain of 10.6dB. Thus, proposed antenna offers an enhanced bandwidth and increased gain simultaneously

Result:

The feeding mechanism has been analyzed using Characteristics Mode Analysis (CMA). CMA shows best possible position for the port feeding. The modal Significance graphs give detail overview about the current distribution of the patch without feeding. In Figure 4 modal significance graphs shows the generation of four modes. It is evident from the graph that mode 1 performed best at the desired operating frequency.

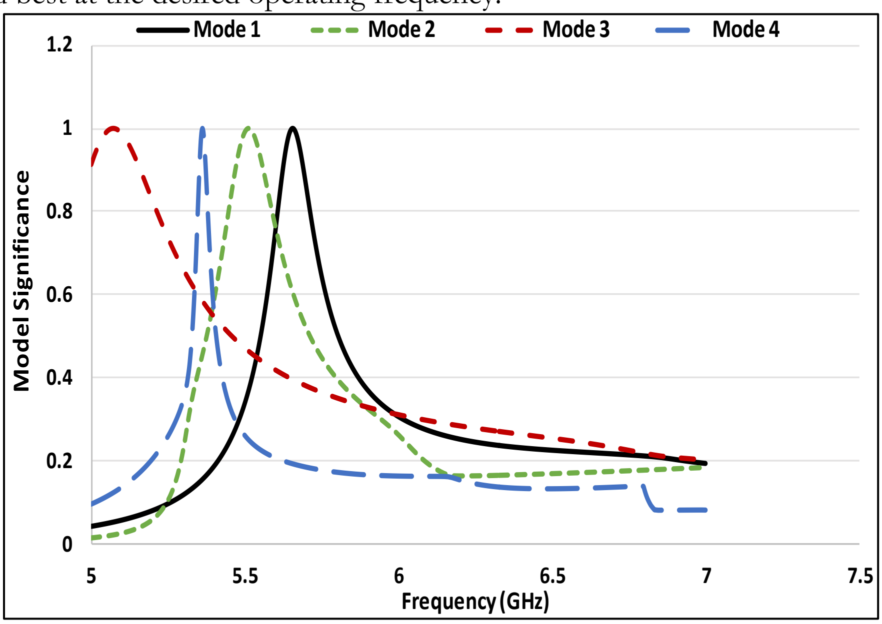

Figure 4: Model significance graph of proposed antenna

In addition, in this paper characteristic mode analysis (CMA) technique is used in order to get optimized position for the feed point. Characteristics mode analysis in Figure 5 shows that at 5.8GHz only mode 1 is passing through 180 angle, therefore mode 1 is best possible mode of the given antenna because the mode nature is determined by eigenvalue λn and it will radiate efficiently at $\lambda n=0$.Eigenvalue $\lambda n>0$ modes are storing magnetic energy and $\lambda n<0$ means storing electric energy. Also, as shown in Figure 6, at 5.8 GHz only mode 1 is passing through value 0 and characteristics angle is equal to 180 as shown in equation. Thus, in Figure 7 we can see that impedance bandwidth of 13.8% is achieved. This improvement in impedance bandwidth is achieved by using slot in the ground structure.

$$\text{Modal significance}=1/(1+j\ \lambda_n) \qquad (2)$$

$$\alpha_n = 180^0 - tan^{-1}(\lambda_n) \quad (3)$$

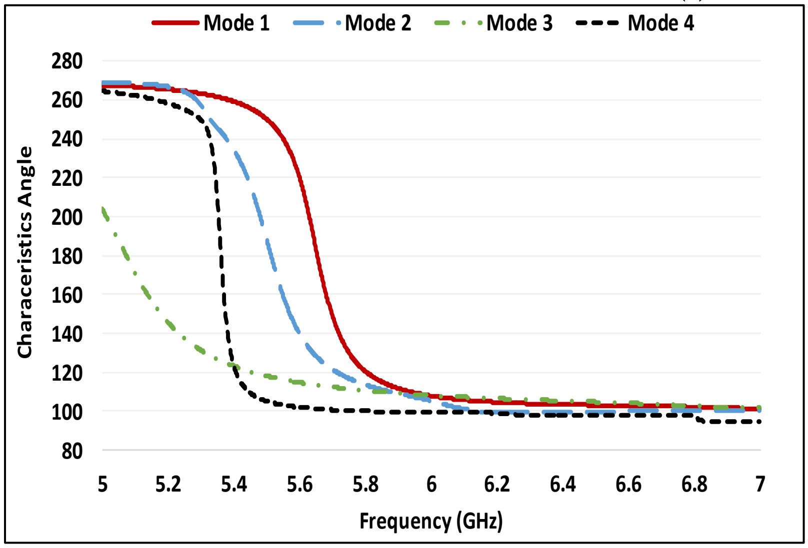

Figure 5: Characteristics mode analysis Mode 1-4

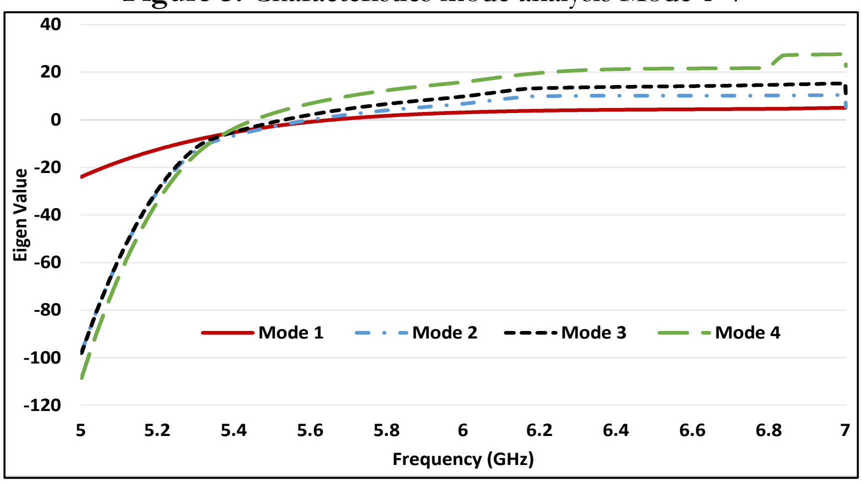

Figure 6: Eigen value graph mode 1-4

By etching DGS structures in the ground plane near the feed point, the antenna bandwidth has been improved. Figure 7 depicts the simulated results of an antenna with DGS. In Figure 8 S parameter results of Antenna with DGS and without DGS are compared. This clearly illustrates that utilizing the DGS approach, the antenna bandwidth is increased from 8.5 to 13.8 %.

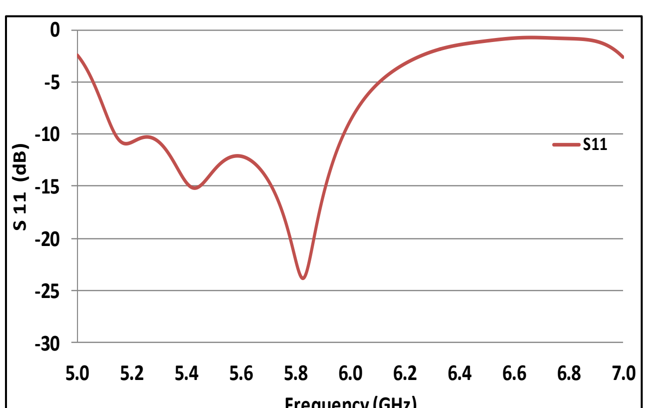

Figure 7: Reflection coefficient (S11) of proposed antenna

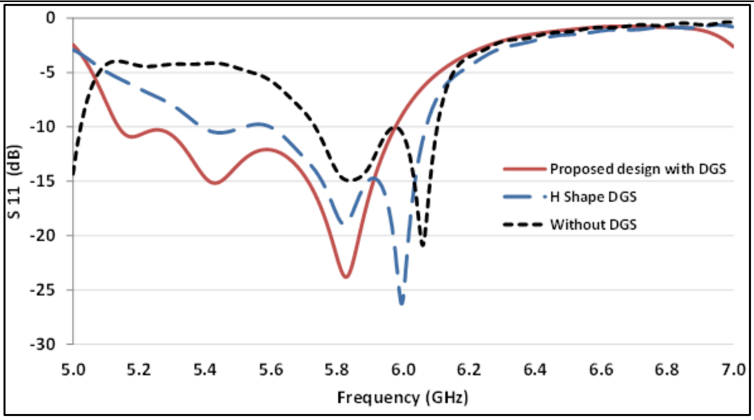

Figure 8: Simulated S11 of proposed Antenna and without DGS Structure.

Moreover, other shapes such as H-Shape slot is also etched and simulated results are obtained, however Figure 8 shows comparison of impedance bandwidth without DGS, proposed structure and with H-shape DGS structure and it depicts that rectangular slot improved the bandwidth of proposed structure.

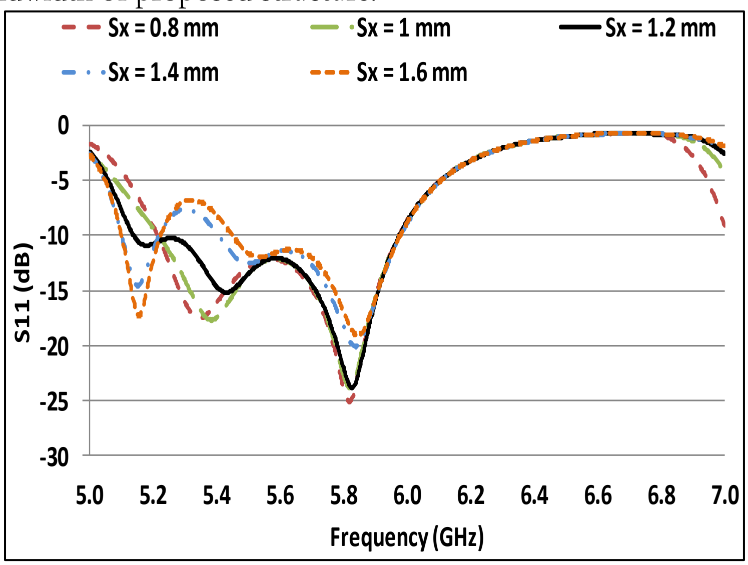

Figure 9: Parametric sweep of DGS Structure on S_x.

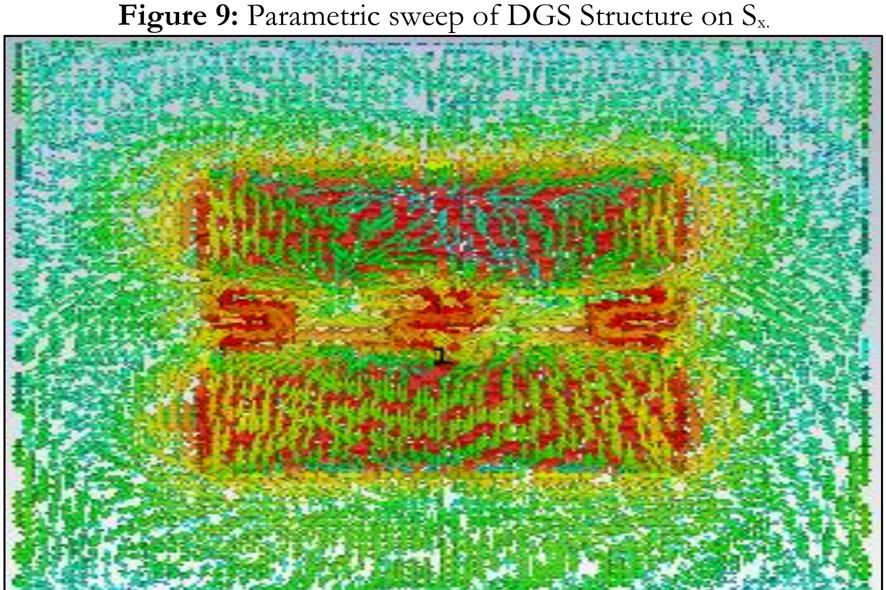

Figure 10: Surface Current Distribution

The parametric analysis of the designed DGS structure for our patch antenna is shown in Figure 9. We applied the parametric analysis on the width of the slot (Sx) parameter of DGS because of its length and width is similar to that of the meandered lines on the opposite side. As it can be observed, maximum bandwidth is obtained at Sx = 1.2, when varied between 0.8mm and 1.6mm.

The Current distribution of the proposed antenna is shown in Figure 10. It shows path of the current flow and thus it can be observed that proposed antenna is operating at TM03 mode due to mender lines. Therefore, TM03 mode is used for exiting the proposed antenna in order to achieve the desired results. Figure 11 shows the maximum gain vs frequency. It can be observed that the gain is greater than 10 and increases to 11 until 6.9 GHz. Thus, it can be seen increase in the bandwidth of our proposed antenna without affecting its gain.

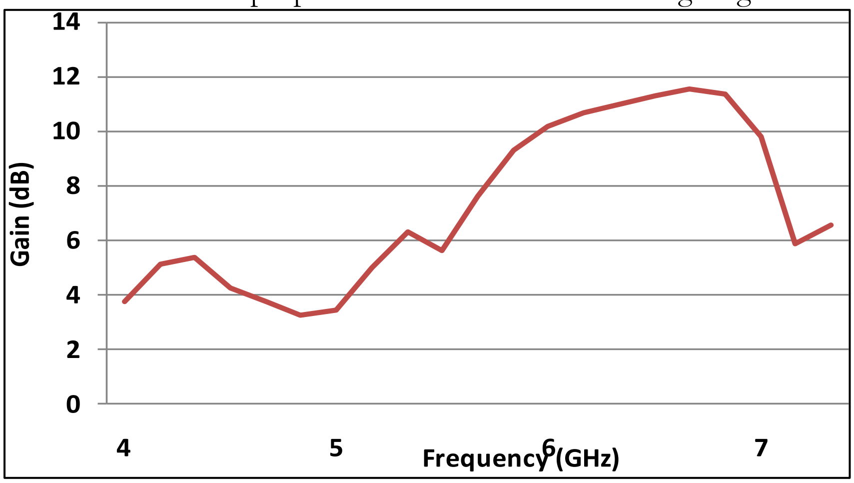

Figure 11: Gain vs Frequency graph

The Simulated results of the proposed antenna have been compared with previous literature work as shown in table 2. It can be seen from the table that our proposed design structure results in an increased bandwidth when compared with the previously proposed studies.

Table 2: Comparison Table

Ref	Frequency (GHz)	Overall size in term of λ_0^2($\lambda_0^2$is the free space wavelength)	10dB- S11 BW (%)	Gain (dBi)
[29]	2.65	$3.13\lambda_0^2$	4.9	14.6
[30]	4.2	$2.37\lambda_0^2$	3.6	12.8
[31]	9.9	$3.08\lambda_0^2$	1.56	9.9
[32]	9.94	$5.52\lambda_0^2$	1.2	13.06
[33]	2.85	$2.61\lambda_0^2$	2.3	10.6
[6]	5.8	$1.70\lambda_0^2$	8.5	10.5
Proposed Design	**5.8**	$\mathbf{1.70\lambda_0^2}$	**13.8**	**10.2**

Conclusion:

This paper focuses on designing microstrip patch antenna operating at higher order mode. A microstrip patch antenna with an overall dimension of 67.5 x 67.5 mm^2 is proposed. Characteristics Mode Analysis (CMA) technique is opted in order to locate best possible feed point. The operating frequency of the proposed Antenna ranges from 5.1 GHz to 5.9 GHz and using the DGS approach and the higher order mode, i.e. TM03 Mode, the antenna's total bandwidth is increased from 8.5 percent to 13.8 percent. Moreover, peak gain of 10.2dB is achieved in the operating bandwidth. In comparison with publish work, our paper marked improved in bandwidth and having structural simplicity. Therefore, proposed antenna could be a good design for communication applications.

References:

[1] R. Chair, C. L. Mak, K. F. Lee, K. M. Luk, and A. A. Kishk, "Miniature wide-band half U-slot and half E-shaped patch antennas," IEEE Trans. Antennas Propag., vol. 53, no. 8 II, pp. 2645–2652, Aug. 2005, doi: 10.1109/TAP.2005.851852.

[2] P. Tilanthe and P. C. Sharma, "An equilateral triangular patch antenna with T - Shaped notch for enhanced gain," Proc. 4th Int. Conf. Wirel. Commun. Sens. Networks, WCSN 2008, pp. 179–180, 2008, doi: 10.1109/WCSN.2008.4772706.

[3] Q. Liu and L. Zhu, "A Compact Wideband Filtering Antenna on Slots-Loaded Square Patch Radiator under Triple Resonant Modes," IEEE Trans. Antennas Propag., vol. 70, no. 10, pp. 9882–9887, Oct. 2022, doi: 10.1109/TAP.2022.3184494.

[4] S. Agrawal and M. S. Parihar, "Bandwidth Enhancement of a Compact Slot Antenna with Frequency Scale Up/down Capability," IETE Tech. Rev., vol. 40, no. 5, pp. 632–640, Sep. 2023, doi: 10.1080/02564602.2022.2144494.

[5] T. Anu and V. Dinesh, "Analysis of Transverse Magnetic Modes in Microstrip Patch Antenna," Asian J. Appl. Sci. Technol. (Open Access Q. Int. J., vol. 2, no. 2, pp. 759–766, Accessed: Aug. 07, 2024. [Online]. Available: www.ajast.net

[6] M. Abbaspour and H. R. Hassani, "Wideband star-shaped microstrip patch antenna," Prog. Electromagn. Res. Lett., vol. 1, pp. 61–68, 2008, doi: 10.2528/PIERL07111505.

[7] R. K. Verma, "Bandwidth Enhancement of an Inverted F-Shape Notch Loaded Rectangular Microstrip Patch Antenna for Wireless Applications in L and S-band," Wirel. Pers. Commun., vol. 125, no. 1, pp. 861–877, Jul. 2022, doi: 10.1007/S11277-022-09581-6/METRICS.

[8] K. V. Pavan and J. Femila Roseline, "Design and Bandwidth Enhancement of Parasitic Patch Antenna and Comparison with U-Slot Microstrip Patch Antenna for GPS Applications," Proc. 2nd Int. Conf. Innov. Pract. Technol. Manag. ICIPTM 2022, pp. 600–605, 2022, doi: 10.1109/ICIPTM54933.2022.9754082.

[9] E. Chang, S. A. Long, and W. F. Richards, "An Experimental Investigation of Electrically Thick Rectangular Microstrip Antennas," IEEE Trans. Antennas Propag., vol. 34, no. 6, pp. 767–772, 1986, doi: 10.1109/TAP.1986.1143890.

[10] E. O. Omoru and V. M. Srivastava, "Bandwidth and Return Loss Improvement Technique Using Double-Material Substrate Cylindrical Surrounding Patch Antenna:Part-I," Int. J. Eng. Trends Technol. - IJETT, vol. 69, no. 12, pp. 252–256, Dec. 2021, doi: 10.14445/22315381/IJETT-V69I12P230.

[11] S. Elajoumi, A. Tajmouati, J. Zbitou, A. Errkik, A. M. Sanchez, and M. Latrach, "Bandwidth enhancement of compact microstrip rectangular antennas for UWB applications," TELKOMNIKA (Telecommunication Comput. Electron. Control., vol. 17, no. 3, pp. 1559–1568, Jun. 2019, doi: 10.12928/TELKOMNIKA.V17I3.9184.

[12] B. Mishra, R. K. Verma, N. Yashwanth, and R. K. Singh, "A review on microstrip patch antenna parameters of different geometry and bandwidth enhancement techniques," Int. J. Microw. Wirel. Technol., vol. 14, no. 5, pp. 652–673, Jun. 2022, doi: 10.1017/S1759078721001148.

[13] S. Tripathi, A. Mohan, and S. Yadav, "Hexagonal fractal ultra-wideband antenna using Koch geometry with bandwidth enhancement," IET Microwaves, Antennas Propag., vol. 8, no. 15, pp. 1445–1450, Dec. 2014, doi: 10.1049/IET-MAP.2014.0326.

[14] P. S. Hall, "Probe Compensation in Thick Microstrip Patches," Electron. Lett., vol. 23, no. 11, pp. 606–607, 1987, doi: 10.1049/EL:19870434.

[15] D. Mitra, D. Das, and S. R. Bhadra Chaudhuri, "Bandwidth enhancement of microstrip line and CPW-fed asymmetrical slot antennas," Prog. Electromagn. Res. Lett., vol. 32, pp. 69–79, 2012, doi: 10.2528/PIERL12032204.

[16] K. S. Ahmad, M. Z. A. A. Aziz, and N. B. Abdullah, "Microstrip Antenna Array with

Defected Ground Structure and Copper Tracks for Bandwidth Enhancement," 2020 IEEE Int. RF Microw. Conf. RFM 2020 - Proceeding, Dec. 2020, doi: 10.1109/RFM50841.2020.9344781.
[17] D. Rusdiyanto, C. Apriono, D. W. Astuti, and M. Muslim, "BANDWIDTH AND GAIN ENHANCEMENT OF MICROSTRIP ANTENNA USING DEFECTED GROUND STRUCTURE AND HORIZONTAL PATCH GAP," SINERGI, vol. 25, no. 2, pp. 153–158, Feb. 2021, doi: 10.22441/SINERGI.2021.2.006.
[18] D. Shashi Kumar and S. Suganthi, "Miniaturization of Microstrip Antenna with Enhanced Gain Using Defected Ground Structures," 2019 Int. Conf. Data Sci. Commun. IconDSC 2019, Mar. 2019, doi: 10.1109/ICONDSC.2019.8817019.
[19] K. Z. Hu, M. C. Tang, M. Li, and R. W. Ziolkowski, "Compact, Low-Profile, Bandwidth-Enhanced Substrate Integrated Waveguide Filtenna," IEEE Antennas Wirel. Propag. Lett., vol. 17, no. 8, pp. 1552–1556, Aug. 2018, doi: 10.1109/LAWP.2018.2854898.
[20] T. Q. Tran and S. K. Sharma, "Radiation characteristics of a multimode concentric circular microstrip patch antenna by controlling amplitude and phase of modes," IEEE Trans. Antennas Propag., vol. 60, no. 3, pp. 1601–1605, Mar. 2012, doi: 10.1109/TAP.2011.2180305.
[21] P. Juyal and L. Shafai, "Sidelobe Reduction of TM12 Mode of Circular Patch via Nonresonant Narrow Slot," IEEE Trans. Antennas Propag., vol. 64, no. 8, pp. 3361–3369, Aug. 2016, doi: 10.1109/TAP.2016.2576503.
[22] Chandan and B. S. Rai, "Bandwidth enhancement of wang shape microstrip patch antenna for wireless system," Proc. - 2014 4th Int. Conf. Commun. Syst. Netw. Technol. CSNT 2014, pp. 11–15, 2014, doi: 10.1109/CSNT.2014.11.
[23] T. Chen, Y. Chen, and R. Jian, "A Wideband Differential-Fed Microstrip Patch Antenna Based on Radiation of Three Resonant Modes," Int. J. Antennas Propag., vol. 2019, no. 1, p. 4656141, Jan. 2019, doi: 10.1155/2019/4656141.
[24] Q. U. Khan and M. Bin Ihsan, "Higher order mode excitation for high gain microstrip patch antenna," AEU - Int. J. Electron. Commun., vol. 68, no. 11, pp. 1073–1077, Nov. 2014, doi: 10.1016/J.AEUE.2014.05.009.
[25] F. A. A. De Souza, A. L. P. De Siqueira Campos, A. G. Neto, A. J. R. Serres, and C. C. R. De Albuquerque, "Higher Order Mode Attenuation in Microstrip Patch Antenna with DGS H Filter Specification from 5 to 10 GHz Range," J. Microwaves, Optoelectron. Electromagn. Appl., vol. 19, no. 2, pp. 214–227, Jun. 2020, doi: 10.1590/2179-10742020V19I2823.
[26] L. Tao et al., "Bandwidth Enhancement of Microstrip Patch Antenna Using Complementary Rhombus Resonator," Wirel. Commun. Mob. Comput., vol. 2018, no. 1, p. 6352181, Jan. 2018, doi: 10.1155/2018/6352181.
[27] V. A. P. Chavali, A. G. Ambekar, A. A. Kadam, A. A. Deshmukh, and K. P. Ray, "Compact Stub Loaded Modified Plus Shape Microstrip Antenna for Broadband Response," Lect. Notes Electr. Eng., vol. 570, pp. 111–117, 2020, doi: 10.1007/978-981-13-8715-9_14.
[28] J. Anguera, A. Andujar, and J. Jayasinghe, "High-Directivity Microstrip Patch Antennas Based on TModd-0 Modes," IEEE Antennas Wirel. Propag. Lett., vol. 19, no. 1, pp. 39–43, Jan. 2020, doi: 10.1109/LAWP.2019.2952260.
[29] X. Zhang, L. Zhu, and Q. Sen Wu, "Sidelobe-Reduced and Gain-Enhanced Square Patch Antennas with Adjustable Beamwidth under TM03 Mode Operation," IEEE Trans. Antennas Propag., vol. 66, no. 4, pp. 1704–1713, Apr. 2018, doi: 10.1109/TAP.2018.2806220.
[30] P. Juyal and L. Shafai, "A High-Gain Single-Feed Dual-Mode Microstrip Disc Radiator," IEEE Trans. Antennas Propag., vol. 64, no. 6, pp. 2115–2126, Jun. 2016, doi:

10.1109/TAP.2016.2543804.

[31] X. Zhang, K. D. Hong, L. Zhu, X. K. Bi, and T. Yuan, "Wideband Differentially Fed Patch Antennas under Dual High-Order Modes for Stable High Gain," IEEE Trans. Antennas Propag., vol. 69, no. 1, pp. 508–513, Jan. 2021, doi: 10.1109/TAP.2020.3006394.

[32] J. Anguera, S. Member, A. Andújar, and J. Jayasinghe, "High Directivity Microstrip Patch Antennas based on TM odd-0 modes," vol. 1225, no. c, pp. 1–5, 2019, doi: 10.1109/LAWP.2019.2952260.

[33] X. Zhang, L. Zhu, and Q. Wu, "Side-lobe-reduced and Gain-enhanced Square Patch Antennas with Adjustable Beamwidth under TM 03 Mode Operation," no. c, 2018, doi: 10.1109/TAP.2018.2806220.

[34] P. Juyal, L. Shafai, and L. Fellow, "A High Gain Single Feed Dual Mode Microstrip Disc Radiator," no. c, 2016, doi: 10.1109/TAP.2016.2543804.

[35] P. Juyal, L. Shafai, and L. Fellow, "Sidelobe Reduction of TM 12 mode of Circular Patch via Non Resonant Narrow Slot," no. c, pp. 1–9, 2016, doi: 10.1109/TAP.2016.2576503.

[36] X. Zhang, S. Member, and L. Zhu, "Gain-Enhanced Patch Antennas with Loading of Shorting Pins," no. c, 2016, doi: 10.1109/TAP.2016.2573860.