Design Of Circular Slot Microstrip Patch Antenna With Thin-line Stub For Wideband And Multiband Wireless Applications

Parvathi K K
M.Tech Student, Dept. of ECE College of Engineering Trivandrum
Thiruvananthapuram, India
parvathykk06gmail.com

Dr. Haris P A
Prof, Dept. of ECE
College of Engineering Trivandrum
Thiruvananthapuram, India
harisabdul.k@cet.ac.in

Abstract—
In this paper, a circular slot microstrip patch antenna with a rotated square patch and two thin-line stubsattached to the back side of the antenna for enhancing bandwidthand operational effectiveness is presented. Results show that the antenna operates from 10.5GHz-18GHz with a reflection coeffi- cient of less than -10dB and obtains better bandwidth(7.5GHz). The gain of the circular slot antenna is 6.6dB, providing good per-formance when compared with the rotated square slot antenna. The antenna is suitable for wideband and multiband wireless applications such as radar and satellite.

***Index Terms*—Microstrip antenna, Bandwidth, Tuning stub.**

DOI Number: 10.48047/nq.2023.21.6.nq23177 **NeuroQuantology2023;21(6): 1785-1794**

I. INTRODUCTION

Microstrip antennas are popular because of their thin pla- nar characteristics. Microstrip antennas are used in wireless communication systems including RFID tags, WLAN and Bluetooth. The advantages of microstrip patch antenna include simplicity, ruggedness, lightness, and small volume. Nowa- days, the most researched issue in wireless communication systems is how to reduce the size of microstrip antennas [6].Several researchers are introducing more effective meth- ods to get lower size antenna. Most microstrip antennas are created from a two-dimensional array of microstrip patches. Microstrip line wires are often used to interconnect the antenna to either the receiver or the transmitter. The application of radio frequency occurs at the antenna or base station(or, with receiving antenna, the received signal is generated). Compact and wideband slotted antennas have drawn a lot of attention because it mainly used in wireless communication systems. Microstrip antennas having appealing qualities like high bandwidth and inexpensive price, simplicity, adaptability, flexibility, compatibility and ease of monolithic integration devices [26-30].

Circular slot microstrip patch antenna with thin-line stub having enhanced impedance bandwidth is depends on the feed- ing techniques [14]. There are 4 types of feeding techniques- Coaxial Probe Feed, Microstrip Line Feed, Aperture Cou- pled Feed, and Proximity Coupled Feed.The coaxial feeding method has advantages such as simple construction and effec- tive feeding. Microstrip Line Feed is simple to manufacture and integrate. This proximity feeding technique offers the maximum bandwidth and minimizes spurious radiation, but it is somewhat difficult to fabricate. The microstrip patch and feed line are connected in the aperture-coupled feeding method through a slot in the ground plane. Pure polarization and minimization of interference are two benefits of this technique. There are many types of fed slot antenna structures available in different shapes may be fractal shaped, circular shaped or square shaped are suitable for different applications and also depending on their performance [22-25]. The impedance of the bandwidth varied by location, width and orientation of the feed line [5].

A large number of printed slot antennas in a variety of configurations have been developed for broadband operations. when the length of the antenna increases and the resonance mode's bandwidth expands, the stub creates a high frequency resonance [20]. The antenna's existing resonance mode and the new resonance mode combine to produce a broader bandwidthwhen they are close enough to each other. As a result, this stub is known as a thin-line stub because it can be used to adjustthe operating frequency for practical purposes. As the width of stub is extended, the bandwidth gradually becomes better until it reaches its maximum value. Advanced wireless communica- tion systems require antennas like Microstrip rectangular patchantenna with a broad bandwidth, high gain and compact size is designed to improve performance over a wide frequency range [9]. When microstrip antennas are equivalent to pairs of magnetic dipoles, the length of the feeding line is decreased bytwo, since the resonant frequency is not inversely proportionalto it [8]. At lower resonance frequencies the length of the slot extends as the frequency and antenna's size is reduced[12], [18], [4], [17].

For enhancing the bandwidth of the microstrip patch an- tenna different methods are adopted, some of these methods are discussed below. In [11], the authors describe a microstrip line-fed, multiple-slot printed antenna with dual-stub loading having a high-frequency range and 4 slabs composed of three slots: a lateral slot, a vertical slot, and a round slot by connecting the two slots. A rotatable planar monopole antenna with slots for RF energy harvesting was discussed [15] and it attains maximum efficiency and good design for UWB applications. In [16], the authors describe a Circular monopole UWB Antenna with Hexagonal Slots of dimensio $27mm \times 20mm \times 1.6mm$ for cognitive Radio application In [3], the authors describe a Reconfigurable cognitive rad ultra-wideband (UWB) tapered slot antenna (TSA), and i reconfiguration operation principle relies upon two concept In [1], the authors describe circularly polarized, unidirection and bidirectional square slot antenna with enhanced axia ratio bandwidth, increased gain, and decreased CPBW. In[2 the authors describe a printed ultra-wideband stepped circul slot with stubs, the antenna exhibiting good impedance matc ing. In [10], the authors describe a circular microstrip pat antenna with slots for C Band applications, and its benefi include size miniaturization, power consumption, simpli ity, compatibility with printed-circuit technology, low profile, lightweight, lower return loss, good radiation properties, small size, a planar structure, and ease of fabrication. By attaching a circular slot to a microstrip patch antenna it affects the bandwidth, resonance frequency, and maximum gain of the antenna. The majority of researchers turn to other methods like fractal approaches since using slots is the greatest way toincrease an antenna's effectiveness. Fractal geometry is also a method for designing broadband and multiband antennas[7], [19]. Use of high permittivity dielectric substrates, reactive or resistive loading, and resistive loading are a few techniques that used to the reduce the size of antennas [13]. The antennas enable flexibility in their design due to the combination of the slot element and switchable feed network [21].

Section II gives the description about antenna design and
geometry followed by antenna analysis in section III, section IV gives the results and discussions followed by section V which gives the conclusion.

II. DESIGN OF ANTENNA

Fig.1(a) and (b) show the geometry of the proposed antenna respectively. A circular slot rotated square shaped microstrip patch antenna designed on an FR4 substrate with a permittivity of ϵ_r=4.4, loss of tangent=0.02, substrate height of 1.6mm and an overall size of 37*mm* 37*mm*. FR4 epoxy is used as a substrate and its advantages are easy fabrication, low cost,and easy availability. The additional thin-line stub is attached to the antenna structure in form of a key for enhancing the bandwidth. The antenna consists of the rotated patch having an overall size 12*mm* 12*mm* and circular slot on one side substrate and the feedline is attached to another side of the substrate.The diameter of the circular slot is 14mm and it depends bandwidth, return loss, gain. Copper is used as material in the metal part since it is twice as conductive as aluminum and six times more conductive than steel.Impedance matching can greatly improve the efficiency of an antenna. Ansys HFSS is the simulation tool used to design this antenna. Ansys HFSS is a 3D electromagnetic software used to design and simulate high-frequency products such as antenna, antenna arrays, etc. The dimensions antenna is calculated by using basic equations of the microstrip patch antenna. Transmission line equations are used to determine the stubdimensions.

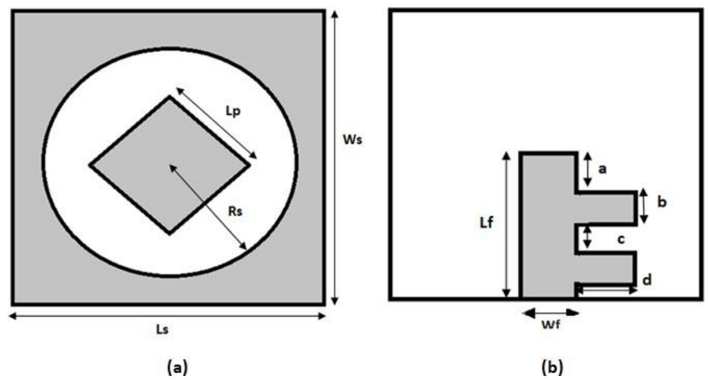


Fig. 1. (a)Top view and (b) Bottom view of the proposed antenna

The parasitic patch is a feed structure for a circular slot microstrip antenna and it acts as a radiator. The stubs have dimensions of length "d", width "b".The two stubs seperated by distance "c". The width "a" is the distance away from the feedline. The impedance matching enhanced at high frequency by introducing stubs to the antenna. The dimensions of the antenna design are given in TABLE I.

TABLE I
DIMENSIONS OF THE MICROSTRIP PATCH ANTENNA(VALUES IN *mm*)

Antenna dimensions	**Values**
Length of the substrate(Ls)	37mm
Width of the substrate(Ws)	37mm
Length of the patch(Lp)	12mm
Radius of the slot(Rs)	14mm
Length of the feedline(Lf)	15mm
Width of the feedline(Ws)	3mm
length of the stub(d)	3.2mm
Width of the stub(b)	1.5mm

Separation of width(c)	2mm
Distance away from the feedline(a)	5.5mm

III. ANTENNA ANALYSIS

A. THEORETICAL ANALYSIS

The microstrip patch antenna structure consists of a rotated square patch and circular slot on the dielectric substrate and the feedline attached with a stub on the back side of the dielectric substrate. For the design of the microstrip patch antenna, we have to select the resonance frequency and dielectric medium and its thickness(h). The dimensions of an antennaare not directly proportional to the dielectric constant of the substrate. In this design, a high dielectric substrate is used which leads to smaller antenna dimensions. The basic structure of the microstrip patch antenna antenna is given in Fig.2. The dimensions of the proposed antenna are calculated by using the basic design formulas of the microstrip patch antenna is given below

The width of the antenna is given by,

$$w = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}}$$

fr-resonant frequency

ϵ_r-relative permittivity

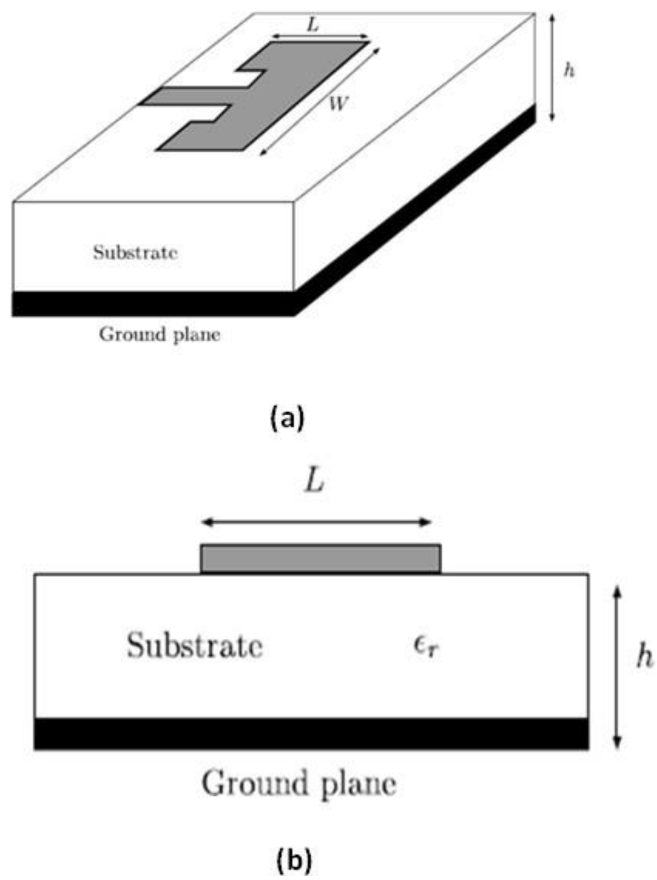


Fig. 2. Basic framework of a microstrip antenna

The resonant frequency of the microstrip antenna is givenby,

$$f=\frac{c}{2L\sqrt{\epsilon_{\text{eff}}}}$$

where *c* is the velocity of light
The effective dielectric constant of the antenna is given by,

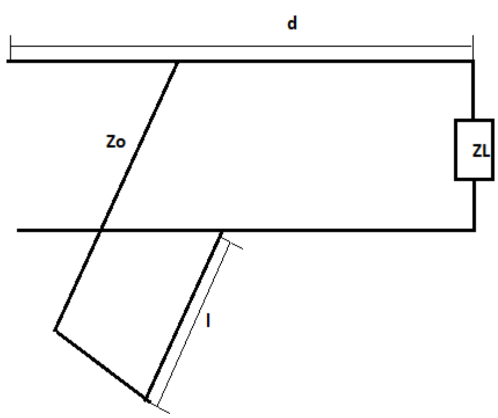
$$\epsilon_{\text{reff}} = \frac{\epsilon_r+1}{2}+\frac{\epsilon_r-1}{2}\frac{1}{\sqrt{\left(1+\frac{12h}{W}\right)}}$$

$$L=\frac{1}{2f_r\sqrt{\epsilon_{\text{eff}}}\sqrt{\mu_0\varepsilon_0}}-2\Delta L$$

$$\Delta L=\frac{(\epsilon_{\text{eff}}+0.3)\left(\frac{w}{h}+0.264\right)}{(\epsilon_{\text{eff}}-0.2583)\left(\frac{w}{h}+0.8\right)}*0.412h$$

The length of the microstrip antenna is given by,
h-height of the dielectric material
μ_0-Permittivity of free space
ϵ_0-Permeability of vacuum

Fig. 3. Configuration of single stub matching



The bandwidth can be varies by making changes in thefeed line even become double by attaching thin-line stubsstubs. When the open circuit stub's length is almost a quarter wavelength. Stub provides dual frequency response is caused by capacitive and inductive impedances, which are capacitive for frequencies below the patch resonance frequency and inductive for frequencies above it. The configuration of single stub matching is depicted in Fig.3.

The dimensions of the stub calculated by using the trans- mission line equations

The location of the stub is given by,

$$l_s=\frac{\lambda}{2\pi}\tan^{-1}\left(\sqrt{\frac{z_R}{z_0}}\right)$$

The length of the stub is given by,

$$l_t=\frac{\lambda}{2\pi}\tan^{-1}\left(\frac{\sqrt{z_R z_0}}{z_R-z_0}\right)$$

Z_R-input impedance
Z_o-characteristics impedance

IV. RESULTS AND DISCUSSION

The Fig.4. depicts the Simulated layout of the proposed circular slot microstrip patch antenna with a thin-line stub having a circular slot attached front side of the substrate anda feed line with stub in the form of the key-like structure attached to the back side of the substrate.

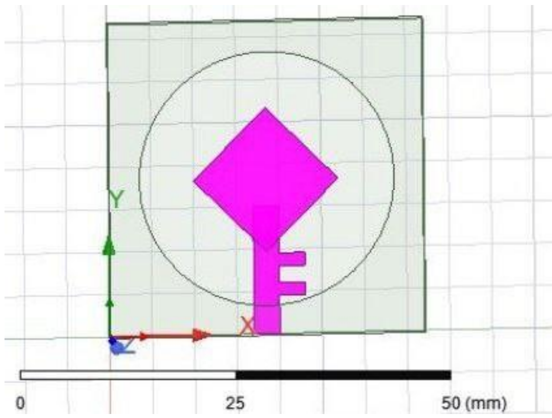


Fig. 4. Simulated layout of the proposed circular slot microstrip patch antennawith thin-line stub.

A. BANDWIDTH

The simulated result reflection coefficient in dB of circular slot microstrip patch antenna with stub and wide band rotated square slot microstrip patch antenna with stub are depicted in Fig.5. and Fig.6. It can be observed that the antenna is resonating from 10.5GHz-18GHz with enhanced impedance bandwidth of 7.5GHz with the reflection coefficient less than -10dB. The bandwidth is enhanced by introducing a circular slot instead of a rotated square slot. By the insertion stub, the bandwidth become double when compared with the normal feed line.

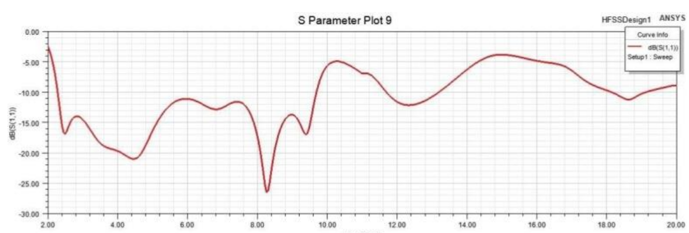


Fig. 5. S11(dB) plot of the wide band rotated square slot microstrip patch antenna with stub

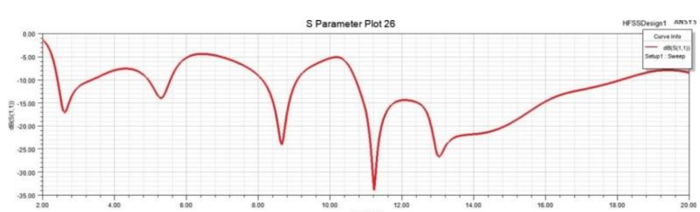


Fig. 6. S11(dB) plot of the circular slot microstrip patch antenna with stub

The TABLE II below shows the Comparison of bandwidth and frequency range for a microstrip patch antenna with different slots. Circular slot have better results compared with square slot.

TABLE II
COMPARISON TABLE OF BANDWIDTH AND FREQUENCY RANGE FOR A MICROSTRIP PATCH ANTENNA WITH DIFFERENT SLOTS

Type of slot	**Max. antenna gain**
Square slot	5.1dB
Circular slot	6.6dB

Type of slot	**Frequency range**	**Bandwidth**
Square slot	2.4GHz-9.26GHz	6.86GHz
Circular slot	10.5GHz-18GHz	7.5GHz

TABLE III
COMPARISON TABLE OF MAXIMUM ANTENNA GAIN FOR A MICROSTRIP PATCH ANTENNA WITH DIFFERENT SLOTS

B. GAIN

The simulated gain plot of circular slot microstrip patch antenna with stub and wide band rotated square slot microstrippatch antenna with stub are depicted in Fig.7. and Fig.8. The results show that the comparison of antenna gain of wideband rotated microstrip patch antenna between the circular slot microstrip patch antenna.Apparently, the square slot antenna can normally provide the peaked gain. On the other hand, by introducing circular slot instead of square slot, it is clearly seen that the higher antenna gain of 6.6dB can be obtained. The antenna gain is varies with different slots. The antenna gain is attained maximum by increasing the slot area.At the receiver, high-gain antennas have the following effects: In- creases the received signal from certain directions and reducesthe signal from others. Gain will also increase the received external noise. The TABLE III below shows the Comparison of maximum antenna gain with different slots in microstrip patch antenna.

C. VSWR

The simulated VSWR plot of circular slot microstrip patch antenna with stub and wide band rotated square slot microstrippatch antenna with stub are depicted in Fig.9. and Fig.10. Theoretically the voltage standing wave ratio(VSWR) at the resonant frequency should be 1, although anything less than 2 is acceptable.As per Fig.10. VSWR reaches 1 at 8.2GHz. The circular slot microstrip patch antenna with stub having better performance because VSWR is 1 for ideal systems. In this antenna actually improves the VSWR more than it decreases the radiation of the antenna. The TABLE IV below shows the Comparison of voltage standing wave ratio with different slotsin microstrip patch antenna.

Fig. 7. Gain plot of the wide band rotated square slot microstrip patch antennawith stub

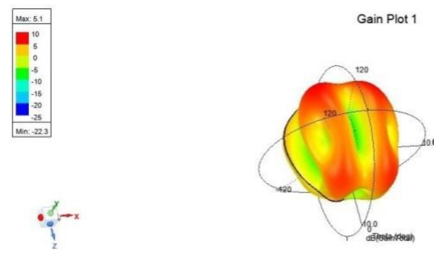
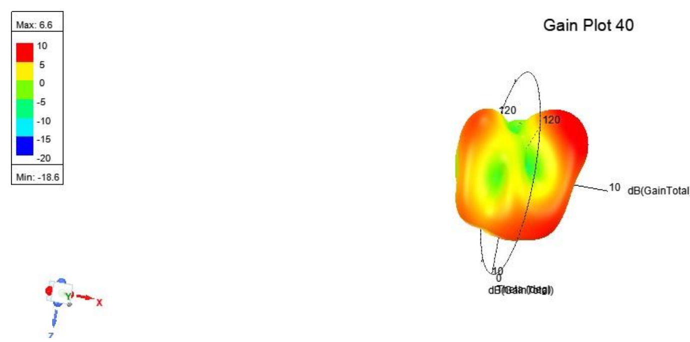


Fig. 8. Gain plot of the circular slot microstrip patch antenna with stub



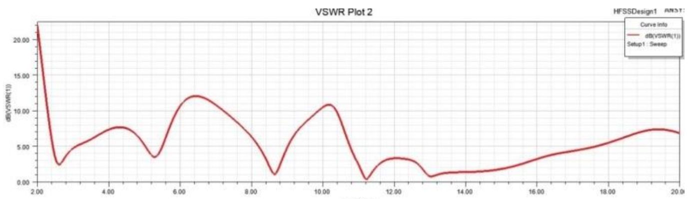


Fig. 9. VSWR plot of the wide band rotated square slot microstrip patchantenna with stub

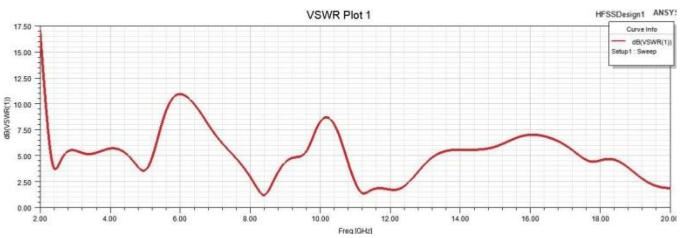


Fig. 10. VSWR plot of the circular slot microstrip patch antenna with stub

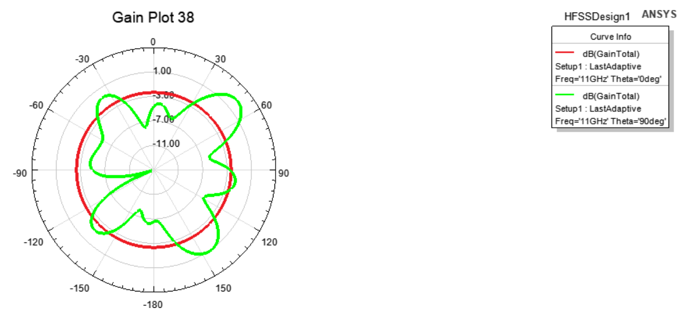
TABLE IV
COMPARISON TABLE OF VSWR FOR A MICROSTRIP PATCH ANTENNA WITH DIFFERENT SLOTS

Type of slot	**VSWR**
Square slot	0.2
Circular slot	1

D. RADIATION PATTERN

The simulated 2-D radiation pattern of the wide band rotated square slot microstrip patch antenna with stub and circular slot microstrip patch antenna with stub are depicted in Fig.11. and Fig.12. The electric field is obtained by taking theta value as 90 degrees and the magnetic field is obtained by taking theta value as 0 degrees. Horizontal pattern and vertical pattern are two resultant patterns of antenna. When the antenna gain increases also the lobe became narrow range The results show that the antenna was found to be an omnidirectional pattern.

Fig. 11. 2-D radiation pattern of the wide band rotated square slot microstrip patch antenna with stub



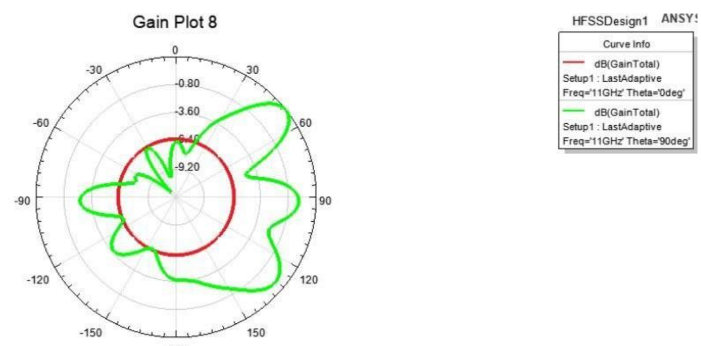


Fig. 12. 2-D radiation pattern of the circular slot microstrip patch antenna with stub

V. CONCLUSION

A circular slot microstrip patch antenna with a pair of tuningstubs for bandwidth enhancement is designed. To improve impedance matching the additional stub is attached to the feedline. Circular slot microstrip patch antenna with stubs have better performance when compared with broad band rotated square slot microstrip patch antenna with stubs. Measurement results indicate that bandwidth enhancement reaches 7.5GHz from 10.5GHz to 18GHz with an antenna gain of 6.6dB. Modern wireless communication applications like radar and satellite may be suitable for the proposed antenna design.

REFERENCES

[1] S. Pan, J. Sze, P. Tu, Circularly polarized square slot antenna with a largely enhanced axial-ratio bandwidth, IEEE Antennas Wirel. Propag. Lett.11

(2012)969–972.

[2] D. Abed , S. Redadaa H. Kimouche (2013) Printed ultra-wideband steppedcircular slot antenna with different tuning stubs, Journal of Electromagnetic Waves and Applications, 27:7,846-855.

[3] D.M.K. Chaitanya, N.V. Koteswara Rao, A reconfigurable ultrawide band(UWB) tapered slot antenna (TSA) with notch for cognitive radio, in: IEEE sponsored second International Conference in Information Embedded and Communication Systems (ICIIECS-15) organized by Karpagam College of Engineering, Coimbatore, during 19-20 March, 2015.

[4] C. Bhan, A. K. Dwivedi, B. Mishra and A. Kumar, ”Quad Bands U-Shaped Slot Loaded Probe Fed Microstrip Patch Antenna,” 2015 Second International Conference on Advances in Computing and Communication Engineering, Dehradun, India, 2015, pp. 409-412.

[5] O. G. Kwame, W. Guangjun, X. X. Lin and M. A. Basit, ”Band- width enhancement of a microstrip-line-fed printed rotated wide slot antenna with tuning stubs,” 2016 IEEE MTT-S International Wireless Symposium (IWS), Shanghai, China, 2016, pp. 1-4.

[6] X. Guo, W. Liao, Q. Zhang and Y. Chen, ”A dual-band em- bedded inverted T-slot circular microstrip patch antenna,” 2016 IEEE 5th Asia-Pacific Conference on Antennas and Propagation (APCAP), Kaohsiung, Taiwan, 2016, pp. 151-152.

[7] S. Sharma, ”A novel compact slotted microstrip patch dual- band antenna with rectangular slotted substrate and symmetrical W-shaped slotted ground having band-notching characteristics for UWB application,” 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), New Delhi, India, 2016, pp. 217-220.

[8] Muduli, R.K. Mishra, Transmission line model for a series fed log-periodic microstrip antenna array, in: 2017 IEEE India Council International Conference(INDICON), Roorkee, 2017, pp. 1–3.

[9] B. Maity, ”Design of dual band L-slot microstrip patch antenna for wireless communication,” 2017 International Conference on Computer Communication and Informatics (ICCCI), Coimbatore, India, 2017, pp. 1-4.

[10] M. H. Reddy, R. M. Joany, G. Manikandan and A. S. A. Nisha, ”Design of microstrip patch antenna with multiple slots for satellite communication,” 2017 International Conference on Communication and Signal Processing (ICCSP), Chennai, India, 2017, pp. 0830-0834.

[11] K.Q. Henderson, S.I. Latif, G. Lazarou, S.K. Sharma, A. Tabbal,
S. Saial, Dual-stub loaded microstrip line-fed multi-slot printed antenna for LTE bands, in: 2018 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting, Boston, MA, 2018, pp. 1743–1744.

[12] S. P. Gangwar, K. Gangwar and A. Kumar, ”A compact mi- crostrip patch antenna with five circular slots for wideband applications,” 2018 3rd International Conference on Microwave and Photonics (ICMAP), Dhanbad, India, 2018, pp. 1-2.

[13] Y. M. Madany, H. M. Elkamchouchi and S. I. Abd-Elmonieum, ”Design and Analysis of Loaded Square Microstrip Patch An- tenna with Shorting Post for Miniaturized Wireless Commu- nication Applications,” 2018 26th Telecommunications Forum (TELFOR), Belgrade, Serbia, 2018, pp. 420-425.

[14] Manikya Krishna Chaitanya Durbhakula, N.V. Koteswara Rao, Wideband rotated square slot microstrip antenna with tuning stub, Materials Today: Proceedings, 2020.

[15] G. Srinivasu, N. Anveshkumar, V. K. Sharma, A circular slotted planar monopole UWB antenna for RF energy harvesting appli- cations, in: 2020 International Conference on Emerging Trends in Information Technology and Engineering(ic-ETITE), Vellore, India, 2020, pp. 1–5.

[16] T. Gayatri, N. Anveshkumar, V.K. Sharma, A Hexagon Slotted Circular Monopole UWB Antenna for Cognitive Radio Appli- cations, in: 2020 International Conference on Emerging Trends in Information Technology and Engineering (ic-ETITE). IEEE, pp. 1-5, Feb. 2020.

[17] E. Li, X. J. Li and Q. Zhao, ”A Design of Ink-Printable Triband Slot Microstrip Patch Antenna for 5G Applications,” 2020 4th Australian Microwave Symposium (AMS), Sydney, NSW, Australia, 2020, pp. 1-2.

[18] P. V. N. R. Teja, M. Raveendra, T. V. Ganesh, J. V. Mahesh and U. Saravanakumar, ”A Multiband Triangular Slot Array based Microstrip Patch Antenna for C X-Band Applications,” 2021 Second

International Conference on Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, 2021, pp.582-585.

[19] Chand, S. Singh and S. Verma, ”Compact Wideband Dual Polarized Circular Slot Antenna for ISM Band Applications,” 2021 10th IEEE International Conference on Communication Systems and Network Technologies (CSNT), Bhopal, India,2021, pp. 19-22.

[20] N. Choudhary, H. Malhotra, N. Kumar and M. Sharma, ”Poly- gon Patch Antenna For UWB And RADAR Applications With Notched Filter Characteristics Realized by inverted T-type stub,” 2021 8th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2021, pp. 637-640.

[21] H. W. Htun, M. Hasan, E. Nishiyama and I. Toyoda, ”A Recon- figurable Circularly-Polarized Ring-Slot Antenna Employing Microstrip-Line Switchable Feed Network,” 2022 International Symposium on Antennas and Propagation (ISAP), Sydney, Australia, 2022, pp. 47-48.

[22] B. V. Naik and D. Nath, ”Design and Analysis of Rectan- gular Slot Microstrip Patch Antenna for Wi-Fi Application at Millimeter-wave Communication,” 2022 IEEE 10th Region 10 Humanitarian Technology Conference (R10-HTC), Hyderabad, India, 2022, pp. 26-31.

[23] S. Hossain, M. S. Rana and M. M. Rahman, ”Design and Anal- ysis of Inverted F-shaped Slotted Patch Multiband Microstrip Antenna for S, C, X, and Ku Band Applications,” 2022 13th International Conference on Computing Communication and Networking Technologies (ICCCNT), Kharagpur, India, 2022, pp. 1-6.

[24] Geetanjali, N. Kashyap and D. Singh, ”Multiband Slotted Cir- cular Microstrip Patch Antenna with Enhanced Bandwidth for Satellite Applications,” 2022 International Mobile and Embed- ded Technology Conference (MECON), Noida, India, 2022, pp.311-314.

[25] S. N. M. Zainarry and D. de Haaij, ”Miniaturization of Circular Ring Slot Patch Antenna for Low Frequency Applications,” 2022 IEEE International Symposium on Antennas and Propa- gation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA, 2022, pp. 379-380.

[26] S. Peters, S. Faghih-Naini, S. Erhardt, T. Reissland and R. Weigel, ”A Planar V-Band Antenna for Wideband Radar and Communication on Low-Cost PCB Substrate,” 2023 IEEE Ra- dio and Wireless Symposium (RWS), Las Vegas, NV, USA, 2023, pp. 153-155

[27] C. Wang et al., ”Ultra-Wideband Millimeter-Wave Bidirectional Circularly Polarized Monopole Antenna Array Using a Sequen- tially Rotated Feeding Technique,” in IEEE Transactions on Antennas and Propagation, vol. 71, no. 1, pp. 1117-1122, Jan. 2023.

[28] I. E. Lamri and A. Mansoul, ”Design of CPW-Fed Dual- Band Four-Element MIMO Microstrip Patch Antenna for WLAN/WiMAX Applications,” 2023 International Microwave and Antenna Symposium (IMAS), Cairo, Egypt, 2023, pp. 83- 86.

[29] G. Montisci, G. Mura, G. Muntoni, G. A. Casula, F. P. Chietera and M. Aburish-Hmidat, ”A Curved Microstrip Patch Antenna Designed From Transparent Conductive Films,” in IEEE Ac- cess, vol. 11, pp. 839-848, 2023.

[30] N. Supreeyatitikul, P. Janpangngern, T. Lertwiriyaprapa, M. Krairiksh and C. Phongcharoenpanich, ”CMA-Based Quadruple-Cluster Leaf-Shaped Metasurface-Based Wideband Circularly-Polarized Stacked-Patch Antenna Array for Sub-6 GHz 5G Applications,” in IEEE Access, vol. 11, pp. 14511-14523, 2023.