Analysis of substrate materials for millimeter wave antenna applications

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Abstract. A compact and novel multi band series fed array antenna is simulated and analyzed for antenna applications in millimeter-wave frequency ranges. The single element antenna performance is investigated for different flexible substrate materials like Rogers Ultralam, Arlon Diclad 880, Neltec NY9220, Taconic TLY, Polyethylene and Polystyrene in initial stages. The proposed series fed array antenna operates (S11<-10dB) in 14.7-20.8GHz, 23.1-25.8GHz, 28.5-34.8GHz and 39.3-44.8GHz frequency bands. The designed antenna exhibits negative group delay characteristics from 18.2-19.9GHz, 29.9-33.3GHz, 39.4-42GHz and 42.6-43.6GHz. It achieved a peak gain of 13.9dB at 42.5GHz and radiation efficiency of 97.5% at 33GHz. Results obtained are in fine conformity and therefore, proposed antenna is preferable for mmwave applications.

1. Introduction

Millimeter waves are grabbing more attention in recent times due to its high data rates, speed and less digital traffic. The millimeter-wave antenna uses the frequency spectrum between 30GHz to 300GHz (or) 1mm to 10mm wavelength range. These antennas were used for military applications since decades, but future 5G communication systems are expected to provide high data-rates that can be used for streaming UHD, 4K and 8K gaming and videos. Conformal antennas for 5G and mmwave applications like airborne, vehicular and cellular facilitate a compact, reliable and robustness of wireless technology. Many researchers proposed various antenna models for conformal applications and millimeter-wave applications and the research work is still in progress.

In [1], a novel broadband, low-profile micro strip antenna array is proposed for mmwave applications. Mm wave antennas for ka, ku bands and 5G applications are proposed in [2-5]. Integrated lens antenna for mmwave applications is proposed in [6] and the authors also investigated the effect of various dielectric materials. In [7-10], design parameters, antenna technologies, different issues and several techniques for 5G mm-wave antennas are proposed. An E-shaped antenna with broadband characteristics and multimode resonance for 5G mm-wave applications is proposed in [11]. A low-cost beam-steerable antenna operating at 28GHz for 5G mobile terminal applications is proposed in [12]. In [13], a Si bulk micro-machined dual-band mm-wave antenna operating at frequencies 60GHz and 94GHz is proposed. A reconfigurable mm-wave antenna for 5G mobile communication it is designed using iterative meandered RF MEMS switch in [14, 15]. In [16], a wideband antenna with high gain of 10.7dBi and narrow beam-width ranging from 23.41-33.92GHz for future 5G communication systems has been presented. Paper [17] presents a meta-surface based wideband circular polarized MIMO antenna. Performance evaluation of conformal array antenna for mm-wave Communications is presented in [18-20]. Antennas using flexible PET substrate for various mm-wave applications are proposed in [21-25]. Transparent fractal antenna for vehicular communications and PET substrate conformal antenna for wireless applications are proposed in [26, 27]. Various conformal micro-strip
patch antennas are designed using split ring resonators, flexible ink-jet printing techniques for various 5G applications in [28-32].

In this paper, a simple and compact series fed 8 element conformal antenna array is proposed for mmwave communications. In section-2, single element rectangular patch antenna is designed from basic design equations and geometric parameters are optimized using parametric analysis. Then antenna is investigated for various flexible substrate materials. Section-3 describes 2, 4 and 8 elements series fed array antenna and their performance characteristics. Section-4 gives conclusion of proposed array antenna.

2. Antenna Design

Millimeter-wave antenna design for conformal applications require the material with low tangent loss and flexible type. Initially, a single element rectangular microstrip patch antenna is designed on Rogers Ultralam of thickness $h = 0.25\text{mm}$ with dielectric constant of 2.17 and loss tangent of 0.0009 in HFSS tool. Substrate dimensions are $L_{\text{sub}} \times W_{\text{sub}} \text{mm}^2$ and length of patch, width of patch and microstrip line feed width are calculated from basic equations of microstrip patch antenna as presented in equations (1) – (5).

Width of microstrip patch $w_{\text{patch}}$ is,

$$w_{\text{patch}} = \frac{c}{2f_{ \text{reso}}} \sqrt{\frac{2}{\varepsilon_{r} + 1}}$$

where, $\varepsilon_{r}$ = relative dielectric constant, $f_{\text{reso}}$ is resonant frequency.

Effective dielectric constant, $\varepsilon_{\text{effective}}$ is calculated as:

$$\varepsilon_{\text{effective}} = \frac{\varepsilon_{r} + 1}{2} + \frac{\varepsilon_{r} - 1}{2} \left[ \left(1 + \frac{12h}{w_{\text{patch}}} \right)^{\frac{1}{2}} + 0.04 \left(1 - \frac{w_{\text{patch}}}{h}\right)^{2}\right]$$

Length of microstrip patch $L_{\text{patch}}$ is given by:

$$L_{\text{patch}} = \left\{ \frac{c}{2f_{ \text{reso}}} \sqrt{\varepsilon_{\text{effective}}} \right\}$$

Input impedance $Z_{\text{in}}$ and width of microstrip line $W_{f}$ are related as:

$$Z_{\text{in}} = \frac{60}{\sqrt{\varepsilon_{\text{effective}}}} \ln \left( \frac{9h}{W_{f}} + \frac{W_{f}}{4h} \right) ; \text{ for } \frac{W_{f}}{h} < 1$$

$$Z_{\text{in}} = \frac{120\pi}{\sqrt{\varepsilon_{\text{effective}}}} \left( \frac{W_{f}}{h} + 1.393 + \frac{2}{3} \ln \left( \frac{W_{f}}{h} + 1.444 \right) \right) ; \text{ for } \frac{W_{f}}{h} > 1$$

From equation (1) - (5), the parameters obtained are: $w_{\text{patch}} = 6.5\text{mm}$, $L_{\text{patch}} = 5.5\text{mm}$ and $W_{f} = 0.77\text{mm}$ for 50ohm input impedance at microstrip line feed. To achieve better performance characteristics, designed single element is optimized using parametric analysis of feed width $W_{f}$. The final design parameters of proposed antenna after parametric analysis are illustrated in table 1. The proposed single element rectangular patch antenna is represented in Figure 1.

| Table 1. Geometrical parameters of single element |
|----------------|----------------|----------------|----------------|-----------|
| Parameter | Size (mm) | Parameter | Size (mm) | Parameter | Size (mm) |
| $L_{\text{sub}}$ | 13 | $L_{\text{Patch}}$ | 5.5 | $L_{f}$ | 3.5 |
| $W_{\text{sub}}$ | 12 | $W_{\text{Patch}}$ | 9.5 | $W_{f}$ | 1.27 |
$S_{11}$ characteristics and parametric analysis for variations in feed width have been represented in figure 2. $W_f = 0.77\text{mm}$ is the nominal value and variations have been observed for $W_f = 0.67\text{mm}$ to $1.47\text{mm}$ with $0.2\text{mm}$ step size. $S_{11}$ characteristics are found to be similar with different values. The characteristics are relatively good for $W_f = 1.27\text{mm}$ with five operating bands $15.35$-$16.7\text{GHz}$, $19.1$-$20.3\text{GHz}$, $26.6$-$30\text{GHz}$, $30.9$-$34.2\text{GHz}$ and $38.2$-$40.4\text{GHz}$ and each operating band has achieved $S_{11} \leq -20\text{dB}$. The familiar mm-wave frequencies $16, 18, 28, 33, 39\text{GHz}$ are achieved by the proposed single element rectangular patch antenna. Further, the proposed single element performance parameters are investigated for various substrate materials Arlon Diclad 880 ($\varepsilon_r = 2.2$ and loss tangent $= 0.0009$), Neltec NY9220 ($\varepsilon_r = 2.2$ and loss tangent $= 0.0009$), Taconic TLY ($\varepsilon_r = 2.2$ and loss tangent $= 0.0009$), Polyethylene ($\varepsilon_r = 2.25$ and loss tangent $= 0.001$) and Polystyrene ($\varepsilon_r = 2.6$), along with
Rogers Ultralam1217 ($\varepsilon_r=2.17$ and loss tangent = 0.0009). All these materials are flexible with low tangent loss and can be used for conformal antenna applications. Figure 3 illustrates $S_{11}$ characteristics of proposed single element antenna for various materials. It is observed that the characteristics are almost similar with minor deviations for the materials other than Polystyrene. The operating bands achieved by different materials are tabulated in table 2. Polystyrene resonates at different resonant frequencies compared to other materials and the minimum $S_{11}$ value is -41.5db at 30GHz.

| Substrate Material | $\varepsilon_r$ | Operating Bands (GHz) |
|--------------------|----------------|-----------------------|
| Rogers Ultralam    | 2.17           | 15.3-16.7, 19.1-20.3, 26.6-30.0, 30.9-34.2, 38.2-40.4 |
| Arlon              | 2.2            | 15.3-16.6, 19.0-20.1, 26.6-29.5, 31.3-34.1, 38.2-40.1 |
| Neltec             | 2.2            | 15.4-16.7, 19.1-20.2, 26.8-29.6, 31.6-34.2, 38.4-40.3 |
| Taconic TLY        | 2.2            | 15.3-16.6, 19.0-20.1, 26.6-29.5, 31.3-34.0, 38.2-40.1 |
| Polyethylene       | 2.25           | 15.1-16.4, 18.8-19.9, 26.4-29.6, 31.1-33.7, 37.8-39.7 |
| Polystyrene        | 2.6            | 14.2-15.4, 17.7-18.5, 24.6-27.0, 28.9-31.4, 35.3-37.1 |

Figure 3. $S_{11}$ characteristics of single element antenna for different materials

Figure 4. Peak gain of single element antenna for different materials
Gain and radiation efficiency characteristics for different materials are represented in figures 4 and 5. Maximum gain achieved for polystyrene material is 9.14dB at 43.7GHz and the maximum peak gain is about 8.1dB for other materials. Radiation efficiency of polystyrene material is higher than other materials and it is about 99%. For remaining materials the radiation efficiency is in between 96-97.5% in operating band. Rogers Ultralam material is considered for further design and analysis of series fed array antenna as it has better $S_{11}$ characteristics which would cover 33GHz applications with reasonable peak gain characteristics and radiation efficiency characteristics.

Figure 5. Radiation efficiency of single element antenna for different materials

3. Series fed array antenna

Series feed technique is the simplest and easiest than parallel or corporate feeding technique for array antennas. To enhance gain of proposed single element antenna, 8 element series fed array antenna is developed and analyzed. Figure 6 illustrates design of 2, 4 and 8 elements series fed array antenna on Rogers Ultralam material. $S_{11}$ characteristics of proposed series fed array antenna are presented in figure 7. From the characteristics ($S_{11}$ < -10dB ) it can be observed that operating bands for three cases are nearly similar with variations in minimum value of $S_{11}$. Operating bands attained by 2-element array antenna are: 14.7-15.6GHz, 16.4-19.3GHz, 23.1-24.9GHz, 29.3-34.8GHz and 38.9-44.5GHz. 4-element array antenna achieved the bands from 14.8-19.3GHz, 19.6-20.9GHz, 22.9-25.6GHz, 28.5-34.7GHz and 39.2-44.8GHz. Similarly, four operating bands 14.7-20.8GHz, 23.1-25.8GHz, 28.5-34.8GHz and 39.3-44.8GHz are achieved by 8-element series fed array antenna. It has better $S_{11}$ values < -20dB at about 18GHz and 33GHz. Further, far-field emission characteristics of proposed 8-element array antenna are investigated at 18GHz and 33GHz.

(i) Antenna array with 2 elements
Figure 6. Series fed rectangular patch array antenna

(iii) Antenna array with 8 elements

take the 2D array as an example, the gain is directional with magnitude 10.2dB at 18GHz and 13.5dB at 33GHz. To investigate cross-polarization and side lobe levels of proposed series fed array antenna at 18GHz and 33GHz resonant frequencies, gain-phi and gain-theta characteristics in E-plane (for Phi=90°) are illustrated in figure 8 and 9 respectively. As the proposed series fed array antenna radiates in E-plane (theta), gain-theta is co-polarization and gain-phi becomes cross polarization. From figure 8, it can be observed that at 18GHz the peak gain-theta is 10.2dB for 𝜃 = −21° and gain-phi is -35.6dB. The minimum acceptable level between co and cross polarizations is 13dB which is achieved by the proposed antenna. HPBW (Half power beam-width) of 18° is achieved from -30.5° to -18.5° in E-plane at 18GHz resonant frequency. E-plane patterns at 33GHz resonant frequency can be investigated from figure 9. Peak gain-theta is 13.5dB for 𝜃 = −45° and gain-phi is -36.8dB. HPBW of 12° is achieved from -51.5° to -39.5°.
Peak gain and radiation characteristics of proposed series fed antenna array with 2, 4 and 8 elements are illustrated in figure 10 and 11. Enhancement in gain is noticed with increase in number of array elements from figure 10. A peak gain of 13.9dB is achieved by 8-element series fed array antenna at 42.5GHz. From figure 11, it is clear that the radiation efficiency ranges between 95-98% in entire operating band.
Figure 10. Peak gain of proposed series fed array antenna

Figure 11. Radiation efficiency of proposed series fed array antenna
Figure 12 illustrates proposed antenna array group delay characteristics to analyze time domain behavior. For 2-element array antenna, group delay is less than 0.3ns except from 18.7-18.8GHz and 30.7-30.0GHz. For 4-element array antenna, group delay is less than 0.3ns except from 18.8-18.9GHz and 32.2-32.6GHz. 8-element array antenna has obtained negative group delay from 18.2-19.9GHz, 29.9-33.3GHz, 39.4-42GHz and 42.6-43.6GHz. Conventional series fed array antennas have a major drawback of beam squint due to variations in phase-shifts with frequencies. From the obtained group delay characteristics of series fed antenna array, group delay among different antenna elements is less than 0.3ns. Therefore, beam squint effect is less for proposed antenna and hence antenna bandwidth is almost retained and boresight gain is also enhanced.

4. Conclusion

In this paper, a novel and compact series fed antenna array is projected for mmwave antenna applications. Single element performance is investigated for different substrate materials like Rogers Ultralam, Arlon Diclad 880, Neltec NY9220, Taconic TLY, Polyethylene and Polystyrene that have similar dielectric constant and loss tangent. Then 2-element, 4-element and 8-element series fed antenna arrays are proposed and simulated. Proposed 8-element planar array antenna operates ($S_{11}<$-10dB) for four operating bands: 14.7-20.8GHz, 23.1-25.8GHz, 28.5-34.8GHz and 39.3-44.8GHz with a peak gain of 13.9dB at 42.5GHz. Radiation patterns in E and H-planes are analyzed for 18GHz and 33GHz resonant frequencies. HPBW is $18^\circ$ and $12^\circ$ at 18GHz and 33GHz respectively. Therefore, projected series fed antenna array is recommended for mmwave applications.

References

[1] Chun-Xu Mao, Steven Gao and Yi Wang 2017 Broadband High-Gain Beam-Scanning Antenna Array for Millimeter-Wave Alications, *IEEE Transactions on Antennas and Propagation* **65** 4864.

[2] Kalyan S. S. S., Kavya K. Ch Sri and Kotamraj Sarat K 2018 Analysis of Synthesized Ka-Band Linear Array Antenna for Beam Steering Alications, *Journal of Mechanics of Continua and Mathematical Sciences* **13**.

[3] Ojaroudiparchin N, Shen M and Pedersen GF 2018 Investigation on the performance of low-profile insensitive antenna with improved radiation characteristics for the future 5G alications, *Microw Opt Technol Lett.* **58** 2148.

[4] Kumar Naik K and Amala Vijaya Sri P 2018 Design of hexadecagon circular patch antenna with DGS at Ku band for satellite communications, *Progress In Electromagnetics Research M* **63** 163.
[5] Kornprobst J, Wang K, Hamberger G and Eibert TF 2019 A mm-wave patch antenna with broad bandwidth and a wide angular range, IEEE Trans Antennas Propag, 65, pp. 4293-98.

[6] Saleem MK, Xie M, Alkanha MAS and Saadi M Effect of dielectric materials on integrated lens antenna for millimeter wave applications Wiley Research Article 1.

[7] Qi Wu, Wang H and Wei Hong 2019 Millimeter-Wave Antenna Designs, Wiley 5G Ref 1.

[8] Yu-Hang Yang, Bao-Hua Sun and Jing-Li Guo 2019 A single-layer wideband circularly polarized antenna for millimeter-wave alications IEEE Transactions on Antennas and Propagation 68 4925.

[9] Rodriguez-Cano R, Zhang S, Kun Zhao and Pedersen GF 2019 Mm-wave beam-steerable endfire array embedded in slotted metal-frame LTE antenna, IEEE Transactions on Antennas and Propagation 68 3685.

[10] Parchin NO, Alibakhshikenari M, Bashlerou HJ, Abd-Alhameed RA, Rodriguez J and Limiti E 2019 MM-wave phased array quasi-yagi antenna for the upcoming 5G cellular communications Al. Sci, Article 9 978.

[11] Jiexi Yin, Qi Wu, Chen Yu, Wang H and Wei Hong 2019 Broadband symmetrical e-shaped patch antenna with multimode resonance for 5G millimeter-wave alications, IEEE Transactions on Antennas and Propagation 67 4474.

[12] Deng C, Di Liu, Yektakhab B and Sarabandi K 2019 Series-fed beam-steerable millimeter-wave antenna design with wide spatial coverage for 5G mobile terminals, IEEE Transactions on Antennas and Propagation 68 3366.

[13] Smriti Agarwal 2020 Design of on-chip compatible concurrent dual band millimeter wave antenna, Progress In Electromagnetic’s Research C 102 213.

[14] Anab M, Irfan Khattak M, Owais MS, Khattak AA and Asif S 2020 Design and analysis of millimeter wave dielectric resonator antenna for 5g wireless communication systems, Progress In Electromagnetic’s Research C 98 239.

[15] Kumar P.A., Rao K.S, and Sravani K.G. 2020 Design and simulation of millimeter wave reconfigurable antenna using iterative meandered rf mems switch for 5g mobile communications, Microsystem Technologies 26 2267.

[16] Ullah H and Tahir FA 2020 A high gain and wideband narrow-beam antenna for 5g millimeter-wave alications, IEEE Access 08 29430.

[17] Hussain N, Min-Joo J, Abbas A and Kim N 2020 Metasurface-based single-layer wideband circularly polarized MIMO antenna for 5G millimeter-wave systems, IEEE Access 08 130293.

[18] Yu Jian Cheng, Hang Xu, Da Ma, Jie Wu, Lei Wang and Yong Fan 2013 Millimeter-wave shaped-beam substrate integrated conformal array antenna, IEEE Transactions on Antennas and Propagation 61 4558.

[19] Semkin V, Bisognin A, Kyro M, Kolmonen V-M, Luxey C, Ferrero F, Devillers F and Raisanen A.V 2015 Conformal antenna array for millimeter-wave communications performance evaluation, Article in International Journal of Microwave and Wireless Technologies.

[20] Semkin V, Ferrero F, Bisognin A, Ala-Laurinaho J, Luxey C, Devillers F and Raisanen A.V 2015 Beam switching conformal antenna array for mm-wave communications, IEEE Antennas and Wireless Propagation Letters 15 28.

[21] Jilani SF and Alomainy A 2016 Planar millimeter-wave antenna on low-cost flexible pet substrate for 5G alications, 10th European Conference On Antennas And Propogation.

[22] Kui Kui Fan and Zhang-Cheng Hao 2016 Cylindrical conformal array antenna with tilted h-plane fan shaped beam for millimeter-wave alication, Microwave and Optical Technology Letters 58 1666.
[23] Javad Pourahmadazar and Tayeb A. Denidni 2017 Millimeter-wave planar antenna on flexible polyethylene terephthalate substrate with water base silver nanoparticles conductive ink Wiley 5G Ref 1.

[24] Naik K K and Gopi Dattatreya 2018 Flexible CPW-fed split-triangular shaped patch antenna for WiMAX alications, Progress in Electromagnetics Research M 70.

[25] Jilani SF, Munoz MO, Abbasi QH and Alomainy A 2018 Millimeter-wave liquid crystal polymer based conformal antenna array for 5G alications, IEEE Antennas and Wireless Propagation Letters 18 84.

[26] Madhav B. T. P., Anilkumar T and Sarat K 2018 Transparent and conformal wheel-shaped fractal antenna for vehicular communication alications, AEU-International Journal of Electronics and Communications 91.

[27] Jilani SF, Abbasi QH and Alomainy A 2018 Inkjet-printed millimetre-wave pet-based flexible antenna for 5G wireless alications, IEEE MTT-S International Microwave Workshop Series on 5G Hardware And System Technologies.

[28] Madhav, Rao M. V and Anilkumar T 2018 Conformal band notched circular monopole antenna loaded with split ring resonator, Wireless Personal Communications 103.

[29] Bandi S, Madhav B. T. P, Nayak D. K and Reddy S. S. M 2019 Compact flexible inkjet-printing antenna on paper and transparent PET substrate materials for vehicular instrument communication Journal of Instrumentation 14.

[30] Ketavath K N and Gopi Dattatreya, Rani S S 2019 In-Vitro test of miniaturized cpw-fed implantable conformal patch antenna at ISM band for biomedical alications, IEEE Access 7.

[31] D Gopi and Naik K K 2019 A low ume flexible CPW-fed elliptical-ring with split-triangular patch dual-band antenna International Journal of RF and Microwave Computer-Aided Engineering 29.

[32] Dattatreya G and Naik K.K 2019 A low ume flexible CPW-fed elliptical-ring with split-triangular patch dual-band antenna International Journal of RF and Microwave Computer-Aided Engineering.