Design of Microstrip Tchebyscheff Phased Array Antennas for Inter-Vehicular Communication

Jibendu Sekhar Roy[1]
[1]School of Electronics Engineering, Kalinga Institute of Industrial Technology (KIIT) Deemed to be University, Bhubaneswar 751024, Odisha, India

Corresponding author: Jibendu Sekhar Roy (e-mail: drjsroy@ rediffmail.com).

ABSTRACT To enhance the safety and comfort of a driver, the wireless technology is used for inter-vehicular communication (IVC). During the lane change in highways, the driver of a high-speed vehicle can exploit the antenna technology using a microcontroller. Here, a 4-element Tchebyscheff phased array of microstrip antennas for IVC application is designed at millimeter wave frequency band of 60GHz. The details of this array design with feed network, its design layout and fabricated prototype are presented. Another 4-element microstrip Tchebyscheff phased array for 6GHz IVC application is designed and the measured result is compared with the simulated result.

INDEX TERMS Array design, inter-vehicular communication, microstrip, radiation pattern, Tchebyscheff phased array.

I. INTRODUCTION

The attention has been paid to the use of wireless systems both for inter-vehicle communications (IVC) and roadside-vehicle communications (RVC) to improve the traffic safety [1-3]. One approach to avoid any accident is to actively support the driver by automatic collection of data by scanning the surrounding environment of the vehicle. In a vehicular safety system, blind spot is the area, where incoming vehicles can't be seen directly by a driver or by the mirror. About 60° is covered by the blind spot area (Fig. 1) with a centre at 30° from the broadside direction. An integrated small radar [4] in the vehicle can scan this area using a phased array antenna. IVC uses different frequency bands including millimeter wave band, like, 60GHz band for vehicular communication.

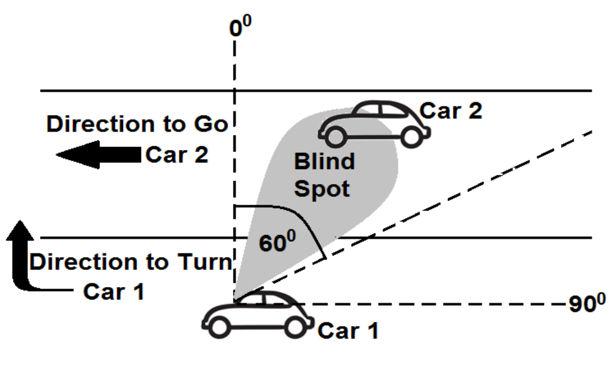

FIGURE 1. Inter-vehicular communication

The 60GHz band is used for short distance communication [5] because of the attenuation of millimeter wave signal due to absorption by atmospheric Oxygen and water vapour.

In a phased array, the radiation beam of the antenna array can be tilted in any desired direction by changing the progressive phase shift between the antenna elements, keeping current amplitudes of all the antenna elements equal. In a Tchebyscheff phased array, both progressive phase shift and current amplitudes of the elements in the array are changed to obtain optimal array pattern in any desired direction for a desired side lobe level (SLL).

In this paper, the design of an antenna system at millimeter wave frequency band at 60 GHz is reported where a 4-element microstrip phased array antenna with array synthesis method Tchebyscheff distribution is used to obtain narrowest beam with a specified side lobe level (SLL). Both the analytical method multi-mode cavity model [6] and optimization technique genetic algorithm (GA) are used for the antenna design. The dimensions of the antenna array with feed network at 60 GHz becomes very small, the Tchebyscheff phased array is designed at the fundamental TM_{10} mode at 20 GHz and will be operated at higher order TM_{30} mode at 60 GHz. For a microstrip antenna both TM_{10} mode and TM_{30} mode have similar types of radiation patterns having broadside maxima because of the current distributions around the edges of the microstrip antenna [6]. At 60GHz, the dimensions of the patch antenna become comparable with the width of a 50

Ohm microstrip feed line. In this situation, undesired spurious radiation from the microstrip line will affect the normal radiation of the microstrip array. Therefore, high impedance microstrip feed lines (lesser line width) are considered to feed the antennas. The design layout including feed network and fabricated antenna array prototype are presented. Because of unavailability of high frequency Network analyzer, measurement could not be done at millimeter wave frequencies. Instead a 4-element microstrip Tchebyscheff phased array antenna with feed network containing equal and unequal ring-type power dividers are designed at 6 GHz and measured results are presented. In 6GHz the dimensions of the patch antenna are several times larger than the width of a 50 Ohm microstrip line and there is no problem to use 50 Ohm feed line at 6GHz. This 6 GHz band is also used for ITS [7] and the designed antenna array at 6 GHz may be useful for inter-vehicular communication.

II. DESIGN OF TCHEBYSCHEFF PHASED ARRAY ANTENNA AT MILLIMETER WAVE FREQUENCY

At high frequency the dimensions of the antenna array becomes very small and in order to minimize the effect of mutual coupling, the H-plane microstrip array is used. The array factor for microstrip phased array is [8]

$$AF = \sum_{n=1}^{N} F(\theta,\emptyset)\ e^{j(n-1)(\frac{2\pi d}{\lambda}sin\theta+\alpha)} \quad (1)$$

Where,

$$F(\theta,\emptyset) = \frac{\sin\left(\frac{k_0 h}{2}\sin\theta\cos\emptyset\right)}{\frac{k_0 h}{2}\sin\theta\cos\emptyset}\ \frac{\sin\left(\frac{k_0 W}{2}\cos\theta\right)}{\frac{k_0 W}{2}\cos\theta}\ sin\theta \quad (2)$$

Here, 'n' is the number of elements, 'd' is the antenna spacing in the array, 'α' is the progressive phase shift. For a microstrip Tchebyscheff phased array, the array factor becomes

$$AF = \sum_{n=1}^{N} T_m(x) F(\theta,\emptyset)\ e^{j(n-1)(\frac{2\pi d}{\lambda}sin\theta+\alpha)} \quad (3)$$

The Tchebyscheff Polynomial $T_m(x)$ is [9]

$$\begin{aligned} T_m(x) &= \cos(m\cos^{-1}x)\ ; && -1< x< +1 \\ &= \cosh(m\cosh^{-1}x); && |x|> +1 \end{aligned} \quad (4)$$

The Tchebyscheff phased array is designed using $T_3(x)$ at the fundamental TM_{10} mode at 20 GHz and will be operated at higher order TM_{30} mode at 60 GHz. A linear Tchebyscheff phased antenna array is designed with 4 microstrip antennas at 6 GHz. The desired direction of main beam is 30^0 from the broadside direction which is required direction of the main beam for the proposed IVC application. RT-Duroid is considered with dielectric constant $\mathcal{E}_r$=2.32, substrate thickness (h)=1.59 mm., tanδ =0.0005.

Multi-mode cavity model using MATLAB is used to obtain the parameters of the microstrp antenna. The rectangular microstrip antenna is designed at 20GHz with feed network at 60GHz, because the antenna will be operated at TM_{30} mode at 60GHz. The antenna array will be operated at TM_{30} mode at 60 GHz and for this TM_{30} mode the variation input impedance at the edges of the patch is more than that of TM_{10} mode [6]. The microstrip feed line width becomes more than the size of the antenna to connect the microstrip patch. Then GA is used along with multi-mode cavity model to determine the dimensions of the patch antenna, appropriate impedance position on the patch where the narrowest microstrip line can be connected with the patch antennas. In GA program, the population size is 20, length of each string is 20 and number of iteration is 50. Length of the antenna varies from 1mm to 6mm. Width of the antenna varies from 1mm to 6mm. The dimensions of the rectangular microstrip antenna at TM_{10} mode at 20GHz are 4.4mmX1.2mm. For this substrate, the guided wavelength at 60GHz is λ_g=3.7mm. The spacing in the array is d=0.5λ_0=0.7λ_g (λ_0=5mm at 60GHz)=2.59mm. The progressive phase shift to tilt the main beam by 30^0 from the broadside direction between successive microstrip antenna elements is α=-βdsin30^0=-126^0. The microstrip line length for 30^0 phase shift is τ=3.7*2.2/2π=1.3mm. The line lengths are (λ_g +mτ), where 'm' is from 0 to 3. The line length of the 1st element is 28λ_g.

To determine Tchebyscheff current distribution for the 4-element microstrip array SLL=-20 dB is considered. If the main beam is in broadside direction (0^0), then the ratios of current in the 4 antennas are calculated [9] as 1: 1.779: 1.779: 1 with three nulls at 30^0, 90^0 and 150^0. When the beam is tilted by 30^0, directivity increases. It is necessary to match the coaxial cable impedance 50Ω to the microstrip antenna feed point impedance 152Ω. For 50Ω, line width =4.35mm. The power from this line is first divided equally between the microstrip antenna elements and different line widths having different impedances and quarter-wave matching transformers are used. The microstrip antenna feed point impedance 152Ω is first matched with an intermediate line of impedance 57Ω (width =3.48mm) with a quarter-wave transformer of impedance Z=√152X57=93Ω (width=1.32mm). Then two parallel lines of 93Ω of are connected with 100Ω by a quarter-wave transformer of impedance Z=√45.4545X100=64.385Ω (width=2.81mm) and power coming from 100Ω line is unequally divided to provide required current ratio as per Tchebyscheff distribution. The power from 50Ω line is equally divided between two 100Ω lines having line width of 1.11mm. Finally, the layout for 4-element microstrip Tchebyscheff Phased array antenna is shown (Fig. 2) with the fabricated prototype (Fig. 3).

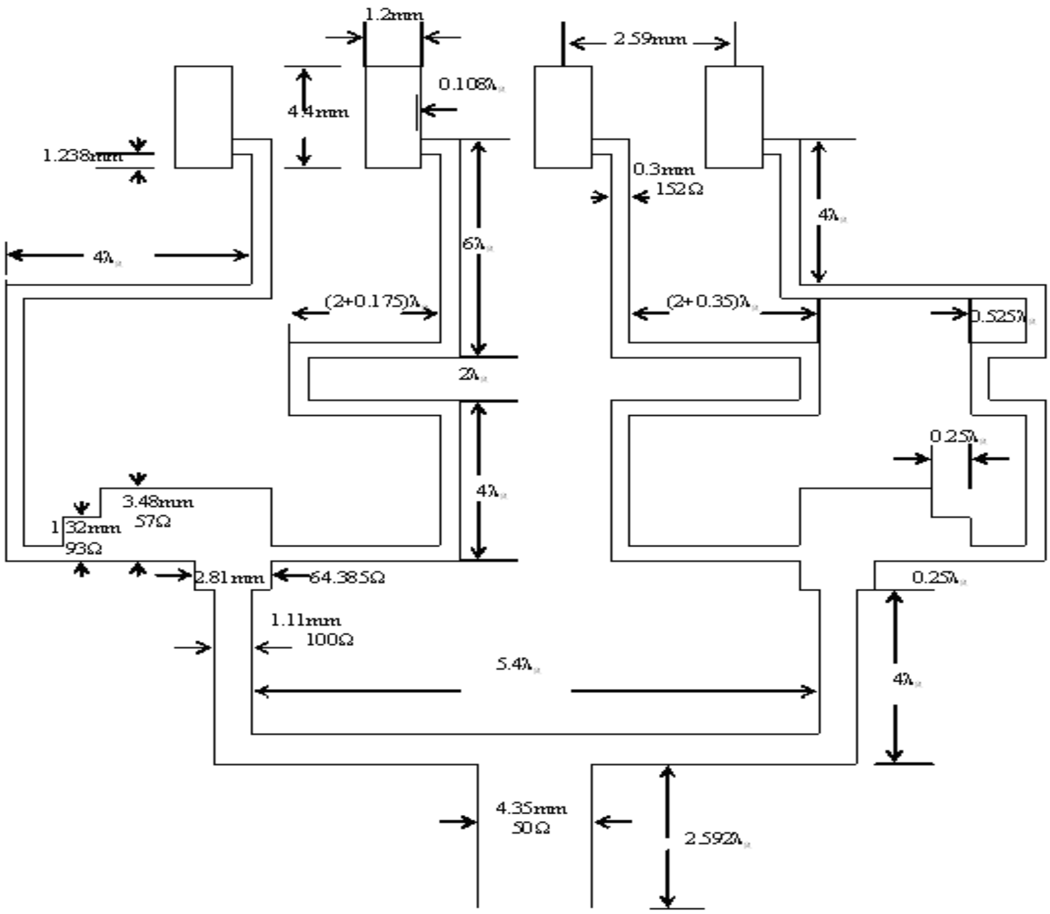

FIGURE 2. Layout for microstrip Tchebyscheff phased array at millimeter wave frequency

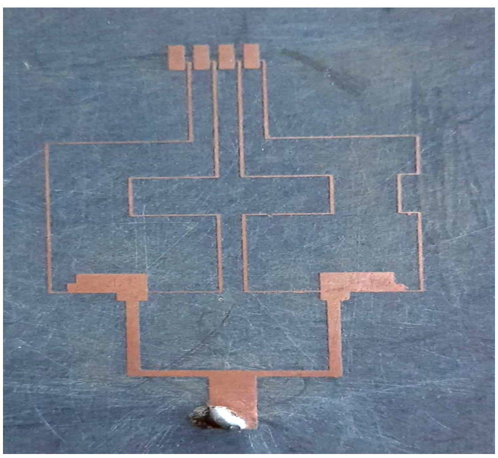

FIGURE 3. Fabricated microstrip Tchebyscheff phased array at millimeter wave frequency

The MATLAB simulated radiation pattern (normalized array factor) for the microstrip Tchebyscheff phased array at 60GHz is shown in Fig. 4, where the beam is tilted at an angle of 30^0 from the broadside direction.

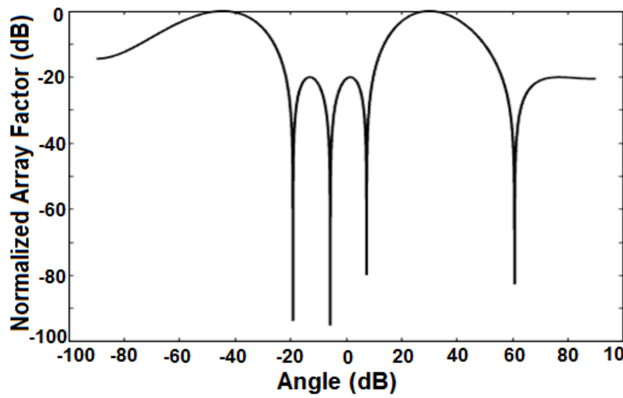

FIGURE 4. Simulated Radiation pattern of microstrip Tchebyscheff phased array at 60GHz

III. DESIGN AND MEASUREMENT OF MICROSTRIP TCHEBYSCHEFF PHASED ARRAY ANTENNA AT 6GHz

A linear Tchebyscheff phased array antenna is designed with 4 microstrip antennas at 6GHz. In Tchebyscheff polynomial, the SLL=-20 dB is chosen. Tchebyscheff polynomial $T_m(x)=T_3(x)$ having 3 nulls. Desired direction of main beam is 30^0 from the broadside direction which for the proposed IVC application. The spacing is $d=0.5\lambda_0$. At 6GHz, effective dielectric constant, $\varepsilon_e=2.132$ and guided wavelength, $\lambda_g=34.2$mm. To tilt the main beam by 30^0, the progressive phase shift is $\alpha=-\beta d\sin 30^0=-126^0$. Corresponding line length is $\tau=34.2*2.2/2\pi=11.97$mm. The line lengths are $(\lambda_g+m\tau)$, where 'm' is from 0 to 3. The line length of the 1^{st} element is λ_g. Tchebyscheff current distribution is 1: 1.779: 1.779: 1. The dimension of the microstrip antenna element is 20mmX16mm, found by cavity model analysis. The antennas were fed at the 50Ω input impedance positions by 50Ω microstrip lines (width=5mm). The array was fed by co-axial SMA connector and first the equal ring-type power divider is used to divide power. Then for unequal current distributions as per Tchebyscheff current ratios, unequal ring-type power dividers are used. Both equal and unequal ring-type power dividers are designed by appropriate design procedure [10, 11]. For equal power divider ring width is 5mm, mean radius is 8.2mm and for unequal power divider, ring width is 5mm and 1.8mm with mean radius of 8.2mm. The Layout for microstrip Tchebyscheff phased array at 6GHz is shown in Fig. 5.

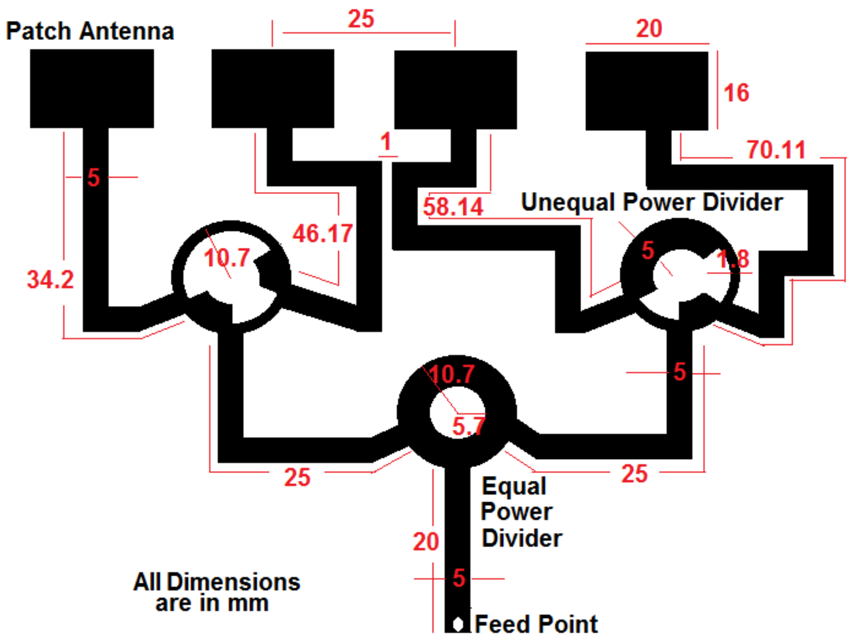

FIGURE 5. Layout for microstrip Tchebyscheff phased array at 6GHz

The fabricated microstrip Tchebyscheff Phased array antenna at 6GHz is shown in Fig. 6.

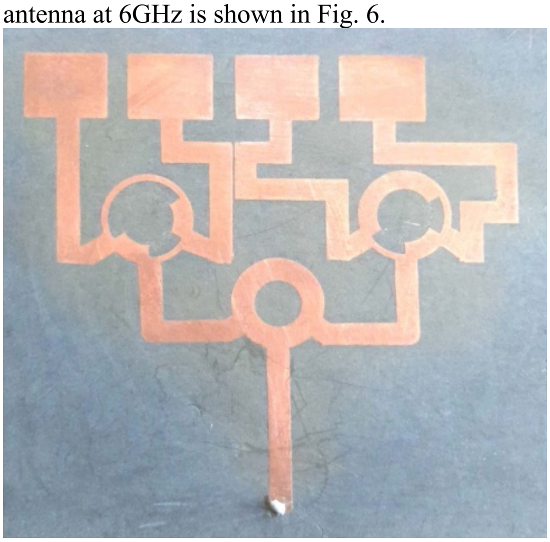

FIGURE 6. Fabricated microstrip Tchebyscheff phased array at 6GHz

The measured radiation pattern is compared with the MATLAB simulated radiation pattern (using (3)) in Fig. 7.

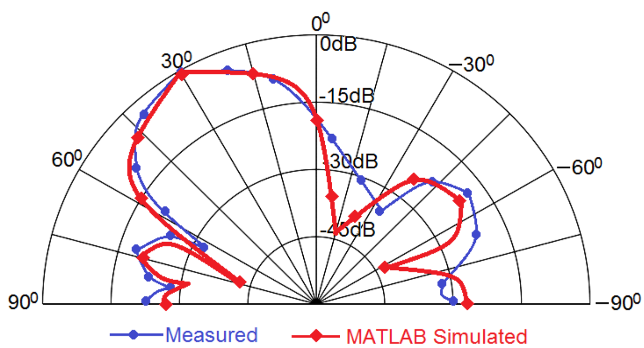

FIGURE 7. Radiation pattern of microstrip Tchebyscheff phased array at 6GHz

C-band Microwave bench with turn table and a pyramidal horn antenna as transmitting antenna is used for the measurement of the radiation pattern. Gain is measured by a VNA by measuring transmission coefficient and using FRIIS transmission formula [12]. The measured gain at 6GHz is 15.5 dB at an angle of 30^0. The simulated directivity of the 4-element microstrip Tchebyscheff phased array at 30^0 is 17.2 dB. The expected theoretical gain of the array is about 16.6dB (considering 85% antenna efficiency for the low loss substrate). The difference between measured and simulated gains is due to losses in the feed network and also due inaccuracy in gain measurement. The measured and simulated radiation patterns agree well.

IV. CONCLUSION

For the design of antenna array at millimeter wave frequency, a new method is used where antenna is designed at 20GHz (at TM_{10} mode) and is operated at higher order TM_{30} mode. Because at 60GHz the dimensions of the patch antenna is very small and become comparable with the microstrip lines and components of the array feed network. The antenna array is an H-plane array which has less mutual coupling effect. Because of the unavailability of very high frequency measuring system, measurement could not be done at 60GHz. In 6GHz antenna dimensions are appreciable, not required to design at higher order mode and so at 6GHz array is designed at the fundamental mode. A 4-element microstrip Tchebyscheff phased array antenna is designed for 6GHz IVC application and measured radiation pattern is compared with the simulated pattern.

ACKNOWLEDGMENT

The author likes to acknowledge AICTE (Gov. of India), New Delhi for providing financial assistance and BIT, Mesra, Ranchi for providing measurement facilities during this work.

REFERENCES

[1] H. Qian, Y. Chen, Y. Sun, N. Liu, N. Ding, Y. Xu, G. Xu,Y. Tang, and J. Yan, "Vehicle safety enhancement system: sensing and communication," *International Journal of Distributed Sensor Networks*, Vol. 2013, pp 1-19, 2013.

[2] S. El Hamdani, N. Benamar, and M. Younis, "A protocol for pedestrian crossing and increased vehicular flow in smart cities," *Journal of Intelligent Transport Systems*, vol. 24, pp. 514-533, 2020.

[3] W. Yu, X. Hua, D. Zhao, W. Wang, and Y. Xiang, "Safety impact of cooperative adaptive cruise control vehicles' degradation under spatial continuous communication interruption," *IET Intelligent Transport Systems*, vol. 16, no.3, pp. 309-331, 2022.

[4] Y. Ju, S. D. Kim, and J. Lee, "Design and implementation of a hybrid digital and RF front-end module for 24-GHz intelligent transport system pulse-Doppler RADAR," *Microwave and Optical Technology Letts*., vol. 55, pp. 1631-1638, 2012.

[5] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-wave propagation channel characterization for short-range wireless communications," *IEEE Trans. Vehicular Technology*, vol. 58, pp.1-13, 2009.

[6] J. R. James, and P. S. Hall, "Handbook of microstrip antennas," Peter Perigrinus, UK, 1989.

[7] S. Maddio, "A compact circularly polarized antenna for 5.8-GHz intelligent transportation system," *IEEE Antennas and Wireless Propagation Letters*, vol.16, pp.533-536, 2017.

[8] A. Halder, A. Senapati, and J. S. Roy, "Smart antenna of microstrip array for sector beamforming for 28GHz millimeterwave mobile communication," *International Journal of Microwave and Optical Technology*, vol. 13, pp.203-208, 2018.

[9] C. A. Balanis, "Antenna theory-analysis and design," New York: Harper and Row Publication; 1982.

[10] J. S. Roy, D. R. Poddar, A. Mukherjee, and S. K. Chowdhury, "On the design and development of ring type microstrip power divider with any desired power division ratio," *Microwave and Optical Technology Letts.*, vol. 2, pp.249-252, 1989.

[11] J. S. Roy, D. R. Poddar, and S. K. Chowdhury, "Broadband design of ring type microstrip power divider," *Microwave and Optical Technology Letts.*, vol.3, pp.119-122, 1990.

[12] J. S. Roy, and M. Thomas, "Investigations on a new proximity coupled dual-frequency microstrip antenna for wireless communication," *Microwave Review*, vol. 13, pp.12–15, 2007.