Micromachined Patch Antenna Array Design and Optimization By Using Artificial Neural Network

Jun Xiao, Xiuping Li*, Hua Zhu, Weiwei Feng and Li Yao

School of Electronic Engineering, Beijing University of Posts and Telecommunications, and Beijing Key Laboratory of Work Safety Intelligent Monitoring, 100876, Beijing, China

* xpli@bupt.edu.cn

Abstract: A 60-GHz 2x2 corporate-fed patch antenna array based on surface micromachined micro-coaxial technology is presented in this paper. The low loss micro-coaxial transmission line is designed to compose the feed network. To improve the bandwidth of the antenna element, a micro-coaxial twin-feed structure with two equal-amplitude and in-phase probes is designed to feed the patch. Artificial neural network (ANN) is applied for antenna element optimization. The 2x2 antenna array shows an impedance bandwidth of 6.5GHz from 57.9 to 64.4GHz under the condition of voltage standing wave ratio (VSWR) less than 2. The gain of the array is 14.5dBi at 60GHz. The total area of the antenna array is 9.58×8mm².

Keywords: patch antenna array, rectangular micro-coaxial waveguide, micromachined, artificial neural network (ANN)

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] P. Smulders: “Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions,” IEEE Communications Magazine, vol. 40, no. 1, pp. 140-147, Jan 2002. (DOI: 10.1109/35.978061).

[2] Hamsakutty Vettikalladi, Waleed Tariq Sethi, and Majeed A. Alkanhal: “High Gain and High Efficient Stacked Antenna Array with Integrated Horn for 60 GHz Communication Systems,” International Journal of Antennas and Propagation, vol. 2014, Article ID 418056, 8 pages, 2014. (DOI:10.1155/2014/418056).

[3] Nadeem Ashraf, Hamsakutty Vettikalladi, and Majeed A. S. Alkanhal, “A DR Loaded Substrate Integrated Waveguide Antenna for 60 GHz High Speed Wireless Communication Systems,” International Journal of Antennas and Propagation, vol. 2014, Article ID 146301, 9 pages, 2014.
[4] K. S. Chin, W. Jiang, W. Che, C. C. Chang and H. Jin: “Wideband LTCC 60-GHz Antenna Array With a Dual-Resonant Slot and Patch Structure,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 1, pp. 174-182, Jan. 2014. (DOI: 10.1109/TAP.2013.2287294).

[5] K. Gong, Z. N. Chen, X. Qing, P. Chen and W. Hong: “Substrate Integrated Waveguide Cavity-Backed Wide Slot Antenna for 60-GHz Bands,” IEEE Transactions on Antennas and Propagation, vol. 60, no. 12, pp. 6023-6026, Dec. 2012. (DOI: 10.1109/TAP.2012.2213060).

[6] Bozzi, M., Pasian, M., Perregrini, L. and Wu, K: “On the losses in substrate-integrated waveguides and cavities,” International Journal of Microwave and Wireless Technologies, 1(5), pp. 395–401. (DOI: 10.1017/S1759078709990493).

[7] T. Seki, N. Honma, K. Nishikawa and K. Tsunekawa: “A 60-GHz multilayer parasitic microstrip array antenna on LTCC substrate for system-on-package,” IEEE Microwave and Wireless Components Letters, vol. 15, no. 5, pp. 339-341, May 2005. (DOI: 10.1109/LMWC.2005.847702).

[8] Y. Saito, M. V. Lukic, D. Fontaine, J. M. Rollin and D. S. Filipovic: “Monolithically Integrated Corporate-Fed Cavity-Backed Antennas,” IEEE Transactions on Antennas and Propagation, vol. 57, no. 9, pp. 2583-2590, Sept. 2009. (DOI: 10.1109/TAP.2009.2027155).

[9] M. V. Lukic and D. S. Filipovic: “Surface-Micromachined Dual Ka-Band Cavity Backed Patch Antenna,” IEEE Transactions on Antennas and Propagation, vol. 55, no. 7, pp. 2107-2110, July 2007. (DOI: 10.1109/TAP.2007.900273).

[10] Jeong-Geun Kim, Hyung Suk Lee, Ho-Seon Lee, Jun-Bo Yoon and S. Hong: “60-GHz CPW-fed post-supported patch antenna using micromachining technology,” IEEE Microwave and Wireless Components Letters, vol. 15, no. 10, pp. 635-637, Oct. 2005. (DOI: 10.1109/LMWC.2005.856690).

[11] Y. Tian, K. Lee and H. Wang: “A 390ps On-Wafer True-Time-Delay Line Developed by a Novel Micro-Coax Technology,” IEEE Microwave and Wireless Components Letters, vol. 24, no. 4, pp. 233-235, April 2014. (DOI: 10.1109/LMWC.2013.2296294).

[12] Tian, Y., Lee, K. and Wang, H. (2014): “Air-gapped microcoaxial transmission line for ultrawide band microwave and millimeter wave ICS,” Microw. Opt. Technol. Lett., 56: 1462–1465. (DOI: 10.1002/mop.28326).

[13] Xuiping Li et al.: “Surface Micro-machined high gain cavity-backed patch antenna array for 60GHz radios,” TENCON 2015 - 2015 IEEE Region 10 Conference, Macao, 2015, pp. 1-4. (DOI: 10.1109/TENCON.2015.7373189).

[14] H. Zhu et al.: “Surface micro-machined high efficient and wideband cavity-backed patch antenna array for 60GHz radios,” 2013 Asia-Pacific Microwave Conference Proceedings (APMC), Seoul, 2013, pp. 316-318. (DOI: 10.1109/APMC.2013.6695131).

[15] J. R. Reid, E. D. Marsh and R. T. Webster: “Micromachined rectangular-coaxial transmission lines,” IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 8, pp. 3433-3442, Aug. 2006. (DOI: 10.1109/TMTT.2006.879133).

[16] Hang Wong, Chi-Lun Mak and Kwai-Man Luk: “High-gain and wide-band single-layer twin-L coupled patch antenna,” The European Conference on Wireless Technology, 2005. Paris, 2005, pp. 71-74.
1 Introduction

Recently, there exists a growing interest in exploiting the 60-GHz band for the applications of indoor short range communications [1]. In this modern era of consumer electronic gadgets, even telephony and cable operated devices in offices and homes are trending towards wireless technology. The demand for higher data rate of these multimedia technologies can be resolved with 60GHz standard as being a viable candidate [2]. Therefore, as one of the 60-GHz technical challenges, antenna design for 60-GHz wireless communications has gained significant attention in recent years. Conductor loss, dielectric loss, surface loss, and degradation caused by transition structures are substantial at millimeter-wave frequencies. Therefore, it’s really a challengeable job to design an antenna with a wide band and high gain at 60GHz [3, 4]. Microstrip arrays are compact, easy to manufacture, cost-effective and easy to integrate with active electronics. However, the microstrip feed networks suffer from high ohmic and dielectric losses at high frequency. Spurious radiations and leakage in the form of surface waves are always major concerns in microstrip antennas and are difficult to handle. All these lead to substantial reduction in gain and antenna efficiency. Substrate integrated waveguide (SIW) or post-wall based planar array antennas have been proposed to realize low cost solutions. This technology enables integration of active circuits together with the antennas. The losses in SIW are lower than microstrip and coplanar structures. Still, losses may be of concern, especially for high-gain (above 30dBi) antennas, due to the presence of dielectric material [5, 6, 7]. Development of microelectromechanical systems (MEMS) over the past decade has provided a solution to the high performance millimeter wave antenna design. In [8], a Ka-band 4×1 corporate-fed patch antenna array is designed with a sequential micro-fabrication technique called PolyStrata process. The antenna achieves a maximum gain of 12.73dBi. In [9], an all copper, recta-coax fed, air-cavity backed dual-band patch antenna is designed with the same process. The maximum gains at 28GHz and 36GHz are 5.1dBi and 5.7dBi, respectively. In [10], a 60-GHz patch array antenna is designed using micromachining process fully compatible with commercial CMOS foundries. The simulated gains of single patch antenna and 2×1 array are 8.7dBi and 9.9dBi, respectively. This paper demonstrates a 60GHz 2×2 patch antenna array built using micromachined micro-coaxial technique. High performance microwave and millimeter wave components, including true-time-delay line [11], transmission line [12], and antennas [13, 14] have already been demonstrated with this technique. Each patch is supported by a metallic post. The technique of parallel feeds is applied to the coupled patch design. A twin-feed structure with two equal-amplitude and in-phase probes is designed to feed the patch. The antenna element is optimized by artificial neural network (ANN). Simulated results show...
that the 2×2 antenna array has achieved an impedance bandwidth of 6.5GHz from 57.9 to 64.4GHz under the condition of voltage standing wave ratio (VSWR) less than 2. The simulated gain of the array is 14.5dBi at 60GHz.

2 Antenna design

2.1 Micro-coaxial transmission line design

Fig. 1 shows the structures of SU-8 strap supported micro-coaxial transmission line. The inner signal line is supported by 20μm thick dielectric straps SU-8 which are placed underneath the inner conductor. The holes in the shielded ground are used for the removal of the sacrificial photoresist. The details of the fabrication of micro-coaxial structure have been introduced in [11, 12]. According to [12], the micro-coaxial transmission line shows less than 0.02dB/mm loss with frequency up to 40GHz. Besides the advantage of low loss, the micro-coaxial structure provides good isolation between the adjacent passive devices because of the fully-shielded structure [12]. The design of the micro-coaxial transmission line starts with the characteristic impedance calculation for different cross sectional dimensions. The characteristic impedance of a transmission line can be calculated as [15]:

\[ Z_0 = \sqrt{\frac{L_{len}}{C_{len}}} = \frac{1}{\nu_p C_{len}} \]  

(1)

Where \( \nu_p=2.998\times10^8 \text{m/s} \) is the phase velocity of the transmission line, and \( C_{len} \) is the capacitance per unit length of the transmission line. The capacitance can be calculated as:

\[ C_{len} = 2\varepsilon \left( \frac{w}{h} + \frac{b}{g} \right) + \frac{4\varepsilon}{\pi} \left[ \ln \left( \frac{g^2 + h^2}{4h^2} \right) + \frac{2}{h} \arctan \left( \frac{h}{g} \right) \right] + \frac{4\varepsilon}{\pi} \left[ \ln \left( \frac{g^2 + h^2}{4g^2} \right) + \frac{2}{g} \arctan \left( \frac{g}{h} \right) \right] \]  

(2)

Where \( \varepsilon = \varepsilon_0 = 8.85\text{pF/m} \). According to the Eq.(1) and Eq.(2), micro-coaxial transmission lines with certain impedance can be designed. The simulation tool is used for a fine tune of the exact dimension in the design. The optimized dimensions of 50Ω micro-coaxial transmission line are listed in Table 1.

Fig. 1. Schematic of unit section of the micro-coaxial transmission line: (a) 3-D view (b) cross-sectional view
| Parameter | Value(μm) |
|-----------|-----------|
| w         | 114       |
| g         | 83        |
| d         | 60        |
| h         | 60        |
| b         | 60        |

Table I. Dimensions of Micro-coaxial transmission line with 50Ω characteristic impedance

2.2 Antenna element design and optimization by ANN

The single probe fed antenna element is designed firstly as shown in Fig. 2. The circular patch is mechanically supported by a metallic post and excited by the extension of the inner conductor. The micro-coaxial transmission line is made a vertical bend for the purpose of miniaturization. It is founded that the extension length $L_{e1}$ of the inner conductor is a key parameter to tune the return loss of the single probe fed antenna element. Fig. 3 shows the effect of $L_{e1}$ on the magnitude of the antenna element’s reflection coefficient $S_{11}$ as a function of frequency. It is observed from Fig. 3 and TABLE II that the center frequency shifts to higher frequency while bandwidth becomes wider as $L_{e1}$ increases. However, the bandwidth is still too narrow to cover the whole 60GHz-band (59-64GHz). It can be concluded that the bandwidth improvement is limited by the existence of the supporting post in the single probe fed antenna design.

Fig. 2. Configuration of the single probe fed antenna element: (a) 3-D view (b) top view (c) lateral view

Fig. 3. Return loss dependence on $L_{e1}$ of the single probe fed antenna element
TABLE II. Simulated results for different values of Le1

| Le1 (μm) | 980 (gap=70μm) | 1010 (gap=40μm) | 1040 (gap=10μm) |
|----------|----------------|-----------------|-----------------|
| Center frequency (GHz) | 60.3 | 60.6 | 61 |
| Bandwidth (GHz) | 2.7 (59.1-61.8) | 3.1 (59.1-62.2) | 3.7 (59.2-62.9) |

To improve the bandwidth of the antenna element, a twin-feed structure [16] with two equal-amplitude and in-phase probes is designed as shown in Fig. 4. The length of the extended feeding inner conductor is not limited by the supporting post anymore which supplies more tuning freedom for the design. According to the design rules of the process, the heights of the patches, inner conductors and ground plane are all set to be 60μm. The ground-signal-ground (G-S-G) testing probe pad is designed as ladder shape for impedance matching as shown in Fig. 4(a), which is the same with single probe fed antenna design.

Fig. 4. Configuration of the proposed antenna element: (a) 3-D view (b) top view (c) lateral view

The micro-coaxial power divider is designed as shown in Fig. 5. For the purpose of miniaturization, the micro-coaxial power divider is made a vertical bend as shown in Fig. 5 (a). As shown in Fig. 5 (b), a vertical bend 35Ω quarter-wave micro-coaxial transmission line is designed for impedance transformation. The width of the inner conductor of 35Ω quarter-wave micro-coaxial transmission line is optimized to be 180μm after careful simulation. The simulated results of the power divider are shown in Fig. 6. It can be seen that the micro-coaxial power divider has broadband matching, equal-amplitude and in-phase power distribution characteristics.

Fig. 5. Configuration of the micro-coaxial power divider: (a) 3-D view (b) top view (perspective view)
Fig. 6. Simulated results of micro-coaxial power divider: (a) S-parameter (b) transmission phase

Several structural parameters are important for the performance of the proposed twin-feed antenna element. Fig.7 shows the effect of the radiating patch radius $R_2$ on the magnitude of the antenna element’s reflection coefficient $S_{11}$ as a function of frequency. It is observed from TABLE III that the center frequency shifts to lower frequency while bandwidth becomes narrower as $R_2$ increases. The extension length of the inner probe conductor is also a key parameter for the antenna element. As shown in Fig. 8 and TABLE IV, $L_e$ affects not only center frequency but also the bandwidth of the antenna element.

Fig. 7. Return loss dependence on the radiating patch radius $R_2$

| $R_2$ (μm) | 1210 | 1260 | 1310 |
|------------|------|------|------|
| Center frequency (GHz) | 64.2 | 61 | 58 |
| Bandwidth (GHz) | 6.2 (60.9-67.1) | 5.9 (58.1-64) | 5 (55.7-60.7) |

Fig. 8. Return loss dependence on the extension of the inner feeding conductor length $L_e$
To obtain the optimal dimensions of the antenna element structure and achieve a fast and accurate design, ANN is used in the simulation design of the antenna element. ANN is an information processing system which has been widely used in the RF and microwave modeling tasks as an unconventional alternative. The multiplayer perceptron (MLP) is a popularly applied neural network structure. A widely used three-layer MLP (3LP) structure which consists of one input layer, one output and one hidden layer [17] is adopted in this paper. The structure is shown in Fig. 9. More details about this structure can be found in [17].

The optimized dimensions are associated to $R_2$ and $L_e$. $R_2$ and $L_e$ for the designed topology range from 1200μm to 1350μm and 1000μm to 1500μm, respectively. The design specification is defined as $S_{11} \leq -10$dB. The optimal simulated results of return loss for the antenna element resulted from HFSS and ANN are shown in Fig. 10. Two results are in good accordance with each other. As seen, simulated -10dB bandwidth from HFSS is 5.9GHz from 58.1 to 64GHz. The simulated gain of the antenna element at 60GHz is 9.1dBi. The optimized dimensions of the antenna element are shown in TABLE V.

| TABLE IV. Simulated results for different values of $L_e$ |
|---------------------------------------------------------|
| $L_e$ (μm)     | 1040 | 1240 | 1440 |
| Center frequency (GHz) | 59.7 | 61 | 62.7 |
| Bandwidth (GHz) | 4.4 (57.6-62) | 5.9 (58.1-64) | 5.1 (59.9-65) |

Fig. 9. The three-layer MLP (3LP) neural network structure [17]

| TABLE V. Optimal dimensions of the proposed antenna element |
|-----------------------------------------------------------|
| Parameter | $W_1$ | $L_1$ | $W_2$ | $R_1$ | $R_2$ | $h_p$ | $L_e$ |
| Value(μm) | 4000 | 4790 | 1086 | 300 | 1260 | 240 | 1240 |

Fig. 10. Simulated results of the proposed antenna element: (a) $S_{11}$ (b) radiation pattern at 60GHz
2.3 Antenna array design

A 2×2 corporate-fed array is designed for additional gain enhancement as shown inFig. 11. Fig. 11(a) shows the three-dimensional (3-D) geometry of the proposed antenna array, and Fig. 11(b) shows the top view. The feeding network consists of several identical T-junction micro-coaxial power dividers as shown in Fig. 5. A U-bend micro-coaxial is designed for 180° phase shift. The distances between patches along x-axis and y-axis directions are 4.3mm (0.87λ) and 4mm (0.81λ), respectively, where λ is the free space wavelength at the center frequency 61GHz. The total size of the antenna array is 9.58×8mm². The simulated results of the antenna array are shown in Fig. 12. As seen, simulated -10dB bandwidth is 6.5GHz from 57.9GHz to 64.4GHz. The gain of the antenna array at 60GHz is 14.5dBi. As shown in TABLE VI, the proposed antenna array features advantages such as wide bandwidth and high gain compared with several reported studies on 60-GHz antenna array.

![Configuration of the proposed 2×2 corporate-fed antenna array: (a) 3-D view (b) top view](image)

![Simulated results of the proposed antenna array: (a) S11 (b) radiation pattern at 60GHz](image)

### 3 Conclusion

This paper demonstrates the design of a 60-GHz patch antenna array built using micromachined micro-coaxial technique. Each patch is supported by a metallic post. The technique of parallel feeds is applied to the coupled patch design. A
twin-feed structure with two equal-amplitude and in-phase probes based micro-coaxial is designed to feed the circular patch. The antenna element is optimized by artificial neural network (ANN). The antenna element is designed covering an impedance bandwidth 5.9GHz from 58.1 to 64GHz under the condition of voltage standing wave ratio (VSWR) less than 2. The simulated gain of a single element is 9.1dBi. An antenna array with 2×2 coupled patch antenna elements is designed to further enhance the antenna gain. Simulated results show that the antenna array has achieved an impedance bandwidth 6.5GHz from 57.9 to 64.4GHz under the condition of voltage standing wave ratio (VSWR) less than 2. The simulated gain of the array is 14.5dBi at 60GHz.

| TABLE VI. Comparison with reported 60-GHz antenna arrays |
|---------------------------------|----------|----------------|-----------------|-----------------|-----------------|
| Ref. | [4] | [5] | [7] | This work |
| Antenna Type | Slot coupled patch array backed with SIW cavity | SIW cavity-backed wide slot antenna | Multilayer parasitic patch array | Patch array |
| Elements Number | 2x2 | 2x4 | 2x2 | 2x2 |
| Process | LTCC | PCB | LTCC | Surface micro-machined |
| Bandwidth (GHz) | 13.8 (54.2-68) | 7 (57-64) | 2 (59.3-61.3) | 6.5 (57.9-64.4) |
| Gain (dBi) | 9 | 12 | 7.17 | 14.5 |
| Size (mm²) | 9.7×6.5 | - | 10×10 | 9.58×8 |

**Acknowledgments**

This work is supported by the projects 61372036 and 61601050 from the National Natural Science Foundation of China (NSFC), the projects of 6140135010116DZ08001 and 6140518040116DZ02001, and the project K201511 from State Key Laboratory of Millimeter waves, Southeast University.