

T-Type Vertical Wall for Decoupling and Pattern Correction of Patch Antenna

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Abstract: The requirements of 5G/6G promote progress in the miniaturization of the antenna array, which promotes the development of a closely spaced decoupling technique. However, the present techniques face the common problem of beam tilt if the spacing is close. Thus, a pattern-corrected, closely-spaced technique is proposed in this paper for the two patch antennas with the $\lambda_0/20$ edge-to-edge distance of the H-plane. The corresponding structure, which is inserted at the center of the spacing, consists of a vertical wall with a single substrate and two symmetrical T-type metals, and a slot at the center is reserved to adequately accommodate the vertical wall. The vertical strip at the other end of the T-type metal is connected to the ground of the patch antenna, while the parallel strip is placed exactly above the patch substrate. After an exact analysis, a prototype was fabricated and measured, and the results showed that the measurements agreed well with those of the simulations, the decoupling coefficients in the 5.8 GHz band were below -20 dB, and the measured radiation pattern at 5.81 GHz was corrected to the broadside from 28° and the maximum realized gain was 5.30 dB.

Keywords: 5G/6G; miniaturization; patch antenna; vertical-wall decoupling; pattern correction



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1. Introduction

The 5G/6G communication technology requires the corresponding devices to be developed in the miniaturization direction, thus promoting this trend in the multi-antenna system, such as the MIMO (Multiple-Input Multiple-Output), phased array. Then, decoupling techniques are necessary when they become closer. Generally, there are three ways to reduce the coupling between patch antennas: (1) Loading metamaterials or dielectrics above the patch [1–3]; (2) adding some novel structures and/or using the defect ground structures between them [4–20]; and (3) through analysis of the field distribution rather than any other structure [21,22].

For the first category, the authors adopted the high-profile structure that placed the loads above the patch to concentrate the radiated field [1,2] or directly on the dielectric to cancel the surface wave for the isolation enhancement [3]. In Reference [1], the near-field resonator consisting of the split rings was proposed, and stronger coupling confines of the H-field generated an orthogonal coupling mode of the E-field to improve the isolation. The primary and secondary reflectors were used above the patch to generate the out-of-phase reflected wave with the coupling wave, which reduced the mutual coupling [2]. While the literature [3] shows that there was a common thick dielectric directly on the patch, the surface wave coupling can be canceled by controlling the space wave coupling through this block.

The most commonly used method for isolation enhancement is by adding planar or three-dimensional structures between the patches. The metamaterial resonator is one of the most common methods to reduce the surface and coupling waves. The authors placed the metamaterial superstrate, where the modified complementary split ring resonators were, between the patches to reduce the surface and space waves [4]. Electromagnetic bandgap (EBG) [5] and the meander-line structures [6–8] were also employed for the same purpose. Additionally, the parallel coupled-line resonators were proposed in Reference [9] to generate the bandstop characteristics and to suppress the coupling. Three interdigital lines were indicated in Reference [10] to form the orthogonal polarization mode on the adjacent patch to enhance the isolation. Except for the mentioned surface wave decoupling techniques, the surface current reduction is another direction to enhance the isolation [8,11–15]. The complete EBG structure separates the common ground plane of patch elements into two parts, which cut off the surface current [8], while the meander line [11] was curved or the fractal technique [12] was used to prevent the surface current. In Reference [13], a slot was proposed to cut the substrate and the ground for the surface wave and current. In Reference [14], the T-shaped and rectangular-ring-shaped defect ground structures were presented to produce the reverse current opposite to the ground coupling current. On the contrary, an etched rectangular slot on the ground plane, to form the band-notch filter with the strip on the top of the substrate to reduce the coupling effectively, was used [15]. The surface current, surface wave, and radiated wave could be blocked together using the vertical wall technique [16]. We also found that the planar filter consisted of a stub-loaded inverted-F radiator to suppress the near-field coupling [17], and the coupled strips close to the feed or the patches were shown to generate another current path for the reduction of mutual couplings [18–20].

The third direction to reduce the mutual coupling was the field analysis of antennas without adding any additional structure. The authors in Reference [21] realized a self-decoupling effect by placing the adjacent patch element into the weak-field area where the coupling strength could be controlled. Two modes were simultaneously excited to generate the specific null-field region to locate the feeding probe at the null field, enabling the designer to achieve extremely low mutual coupling [22].

While excellent isolations have been achieved by using so many techniques, one common problem exists, namely radiation pattern beam tilt after decoupling. This often happens for edge-to-edge spacings larger than $0.1 \lambda_0$ [4,6,12,17,19,21,22], and this always involves a distance of approximately $0.05 \lambda_0$ [3,9–11,13–16,18,20]. This tilt affects the antenna gain in the broadside direction and the whole performance of the corresponding array. Thus, correcting the tilt towards the broadside direction for a closely spaced antenna array is necessary, and this is also the present focus for the miniaturized antenna array design.

A method to correct the pattern for the single frequency was proposed using the vertical wall. However, the realized gain was very low and reduced significantly in the proposed structure [23]. In this paper, the substrate was replaced by a lower loss tangent material F4BTM440 for the patch antenna to obtain a higher realized gain, and a single substrate vertical wall for simplifying the decoupling structure was used to realize the pattern correction at a single frequency. At the same time, the method to improve the antenna gain is also discussed in the following. The vertical wall for decoupling consists of a rectangular substrate inserted into the antenna substrate, and two symmetrical T-type metal strips are etched on the wall. In addition, a long rectangular slot is cut on the antenna substrate to hold the wall where the T-type metal is connected to the ground plane. The structure simultaneously affects the surface current, surface wave, and radiated power to reduce the mutual coupling. Proper T-type metal size is used to adjust the resonator to the desired frequency, and radiation pattern correction is realized at this frequency. The general step for the proposed technique is considered to be: (1) Conventional patch antenna design with a given close spacing, which is taken as the benchmark for the decoupling structure; (2) lossy-wall substrate determination, this determines the realized gain and

the corresponding pattern correction; and (3) resonator design on the wall, the proper dimension of the resonant structure associated with the final decoupling and correction. Depending on these steps, we can migrate this technique into the specific frequency of the 5G/6G application.

The rest of this paper is organized as follows. In Section 2, we introduce the whole configuration of the antenna and the corresponding decoupling vertical wall and discuss the influence factors on the antenna performance by using parametric analyses, including the dimension effect of the vertical wall and the wall substrate losses. The antenna prototype is subsequently fabricated, as shown in Section 3, and then the corresponding simulated and measured results are compared to validate the design, while the comparisons with other designs are provided later. Finally, the current distribution comparison is also shown. After these, the decoupling mechanism and equivalent circuit analysis are indicated in Section 4. The conclusion is provided in Section 5.

2. Antenna Configuration and Parametric Analysis

For the proposed decoupling technique, the corresponding structure consists of two patch antennas with close spacing, the vertical decoupling wall with a single substrate, and a long slot in the antenna substrate to fix the relative vertical wall. After defining the antenna parameters, the parametric analyses for crucial variables are investigated.

2.1. Configuration

The configuration of the proposed vertical wall is shown in Figure 1, where Figure 1a,b correspond to the whole structure and its side view, and Figure 1c,d indicate the details of the designed decoupling wall. The patch antennas are parallel along their H-plane with an inner edge-to-edge spacing of 2.58 mm, which is about $\lambda_0/20$. The two symmetric T-type metal strips are etched on a dielectric substrate wall and inserted between the patch elements forming the vertical wall in the middle. A rectangular hole is cut on the substrate of the radiating patches to accommodate the vertical wall exactly. It should be clear that the vertical metal wall is connected to the ground plane of the radiating patches.

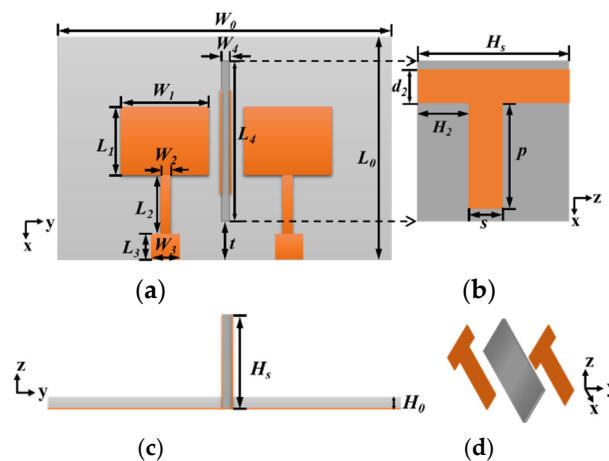


Figure 1. Antenna configuration and decoupling wall: (a) The whole structure, (b) side view of the proposed antenna, (c) front view of the wall, and (d) detailed wall.

The patch antenna is a conventional rectangular that is fed by microstrip lines, as shown in Figure 1a. A quarter-wave transformer is employed between the feeding strip and patch to adjust the impedance matching. The substrate is F4BTM440 with a thickness of 1.6 mm, and the corresponding dielectric constant and loss tangent are 4.4 and 0.0033, respectively. The vertical wall substrate has a higher loss whose loss tangent is 0.025 from the FR4 to increase the dielectric loss on the wall. As mentioned above, the two symmetrical T-shape metals are etched on both sides of the FR4.

Depending on the above structure, we obtained the final values for the related variables shown in Figure 1 by Ansys HFSS 2019, as listed in Table 1. The value of H_2 is 1.9 mm, which is a little higher than the thickness of 1.6 mm of the antenna substrate. This means that the parallel strip of the T-type metal is not immersed in the substrate, so its primary function is to suppress direct radiation to the adjacent element.

Table 1. Values of the antenna variables.

Variable	Value (mm)	Variable	Value (mm)	Variable	Value (mm)
W_0	46	L_2	7.5	p	14
L_0	31.7	W_3	3	t	6.25
H_s	6.4	L_3	3	s	1.98
W_1	15	W_4	0.8	d_2	3.1
L_1	11.5	L_4	20	H_0	1.6
W_2	0.5	H_2	1.9		

2.2. Parametric Analyses

It should be noted that the original design is kept unchanged (patch and feed are fixed). Only changes on the vertical wall are performed to reduce the mutual coupling and to correct the pattern. Five variables are considered for the coupling reduction. These are: The wall height H_s , T-type metal widths d_2 and s of the vertical and parallel strips, and length H_2 and p of the corresponding strips. The upper length of the vertical strip is relative to H_2 and s , which can be obtained at the height H_s ($H_s - H_2 - s$). Thus, the corresponding variable is not shown in Figure 1c. All five variables affect the decoupling and correction; however, they are correlative if the height H_s is determined. As increasing H_2 is equivalent to increasing p for the resonant length at the desired frequency because the induced current flows starting from the H_2 part and ending on the p part. Therefore, only two key variables are selected, d_2 and H_2 , to analyze their influences on the S-parameters and radiation patterns where d_2 mainly affects the surface current from the ground plane, while H_2 is related to the radiation and surface waves.

The effects of the two variables on the antenna performance are shown in Figures 2 and 3, respectively. These comparisons show that these two variables affect the transmission coefficient S_{21} s and the pattern correction, while almost not affecting S_{11} s. Thus, we must carefully adjust the two variables to achieve excellent decoupling in the desired frequency band. Meanwhile, the variable d_2 is more sensitive than that of H_2 to the radiation pattern correction to some extent because it can adjust the radiation pattern of both sides of the broadside direction, while H_2 only corrects the positive side for these given values.

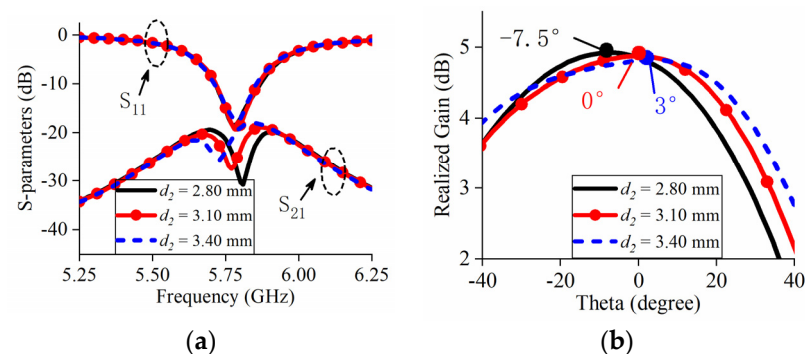


Figure 2. The effect of d_2 on antenna performance: (a) S-parameters and (b) radiation patterns.

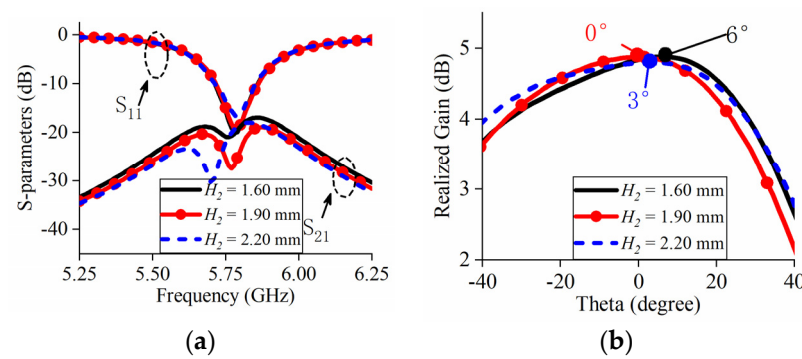


Figure 3. Effect of H_2 on antenna performance: (a) S-parameters and (b) radiation patterns.

However, the wall substrate's property is another factor that affects the final decoupling and pattern correction. Furthermore, we know that the permittivity of this substrate will affect the corresponding resonant length of the concerned frequency, which will be stated in Section 4. Therefore, we do not discuss its influence. In contrast, the loss tangent of the wall substrate will be a key factor to be considered here because we can choose the material with other losses. Figure 4 shows this influence by comparing three different loss tangents, where $\tan \delta = 0.025$ is the general value of the chosen conventional FR4. The results depict that the loss tangent affects not only the S-parameters, but also the realized gain at the concerned 5.80 GHz and its tilt. The lower loss, $\tan \delta = 0.002$, than the one used can improve the realized gain to get closer to that of the no-decoupling structure, which will be presented for the realized gain comparison in the following, but the pattern tilts to -20° , and the decoupling and matching results are not good. Briefly, we can improve the realized gain by the lower lossy substrate, and realize the pattern correction by redesigning the decoupling structure according to this fixed value if the corresponding resonance is formed by the wall–substrate permittivity.

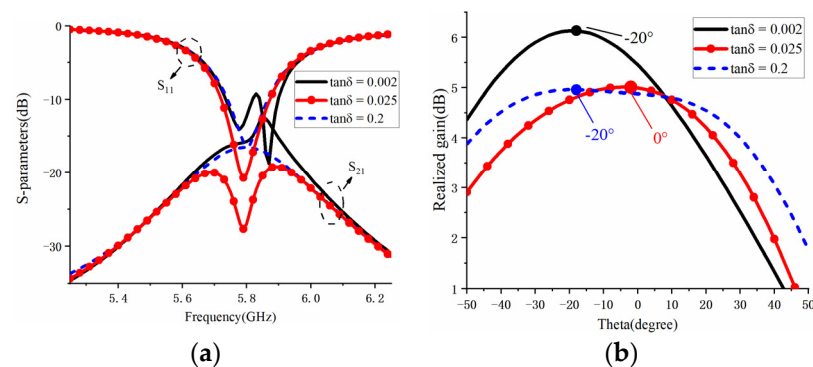


Figure 4. Wall substrate effect on antenna performance: (a) S-parameters and (b) radiation patterns and gain at 5.80 GHz.

3. Result Analyses

Following the above results, one antenna prototype is fabricated and measured in the anechoic chamber to validate the above design. The comparisons between simulated and measured results are presented next, and the differences accompanying the corresponding results are discussed.

3.1. S-Parameters

The antenna prototype is shown in Figure 5. Figure 6 shows the comparisons of the simulated no-decoupling results with the proposed ones, and the comparisons between the simulated and measured results of the proposed structure. It is clear that the proposed method changes the resonant frequency to the higher, and the matching becomes a little

worse than that of a no-decoupling structure, but it is still good. In contrast, the mutual reduction is significant. The simulated S_{21} of no-decoupling structure is higher than -10 dB in the desired frequency band, but it decreases to lower than -20 dB after using the proposed structure.

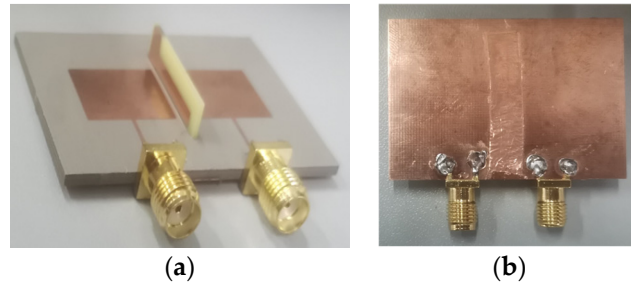


Figure 5. Antenna prototype: (a) 3D view and (b) back view.

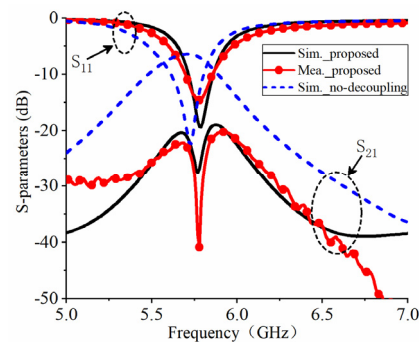


Figure 6. S-parameters comparisons between the simulation, measurement and the no-decoupling.

However, the measured results agree with the simulated results for S_{11} and S_{21} . The corresponding resonant frequencies are almost the same. Though the matching becomes a little worse than the simulation, the bandwidth becomes wider. In any case, we note that the measured coupling is better than the simulation in the concerned band.

3.2. Pattern and Realized Gain

The radiation patterns are measured in the anechoic chamber, as shown in Figure 7, which includes the measurement environment and the fixed detail for the patch. The Agilent N5244A network analyzer, working in 10 MHz~43.5 GHz, is employed in the measurement. The corresponding patterns at the corrected frequencies are presented in Figure 8. The corrected frequency for the simulated result of the proposed structure is 5.80 GHz, while the measured frequency is 5.81 GHz. In any case, the co-polarizations of the no-decoupling structure are also presented for comparison purposes.

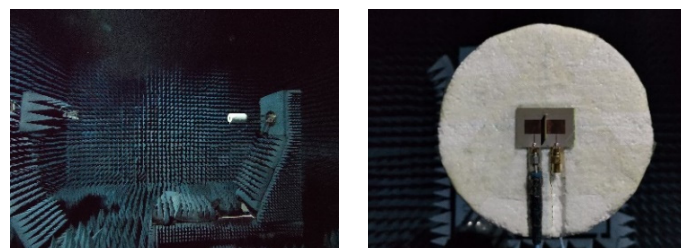


Figure 7. Measurement in the anechoic chamber.

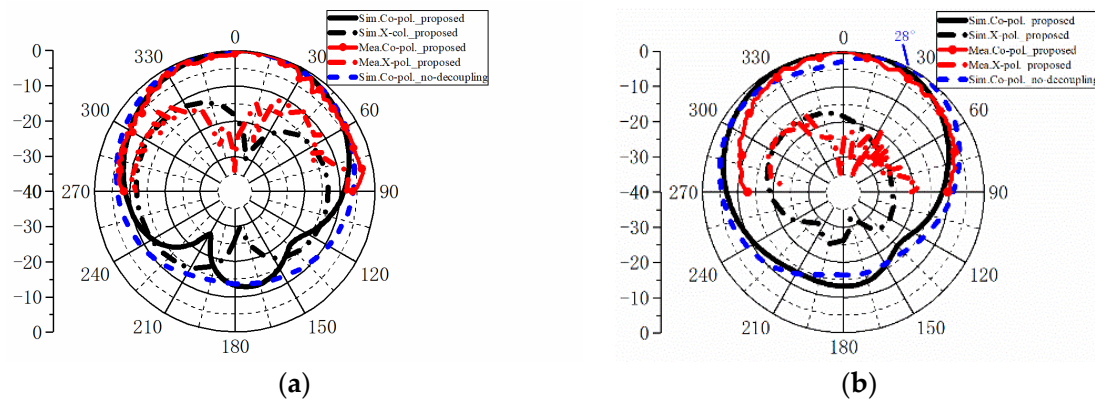


Figure 8. Pattern comparisons between the simulation and measurement: (a) E-plane and (b) H-plane.

In order to state the pattern-corrected direction, we used the negative degree to indicate the radiation tilts to the left of the antenna, as shown in Figure 1a, and the positive degree means the right hand. The radiation patterns are shown in Figure 8 when the left antenna is excited.

Owing to the arrangement of patches along the H-plane, it is easy to judge that the close spacing influences the H-plane radiation pattern, while the E-plane pattern is unaffected. Thus, the H-plane patterns shown in Figure 8 indicate the decoupling effect, while the E-plane is unaffected. The H-plane beam tilts by 28° with no decoupling structure and is corrected to the broadside direction by the T-type wall.

The measurements agree well with the simulation for both the E- and H-plane patterns. Both the co- and the cross-polarizations have good consistencies for the E-plane pattern. A difference is noticed in the co-polarized H-plane patterns, where measured and simulated beamwidths are $-35^\circ \sim 41^\circ$ and $-60^\circ \sim 42^\circ$, respectively. The measurement environment affects the left beam, especially the foam and tape.

Simulated and measured realized gain comparisons are depicted in Figure 9. Here, the corresponding result of the no-decoupling structure is also included. The realized gain decreases by over 2 dB, owing to the existence of the proposed decoupling structure, but the measurement has a good agreement with the simulated results. The maximum difference is 0.28 dB, where the simulated maximum is 5.02 dB at 5.77 GHz and the measured 5.30 dB at 5.81 GHz. The fabrication causes this difference because we cannot mount the vertical wall precisely, as in the simulation.

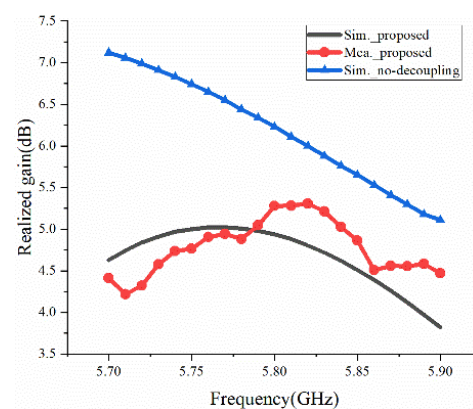


Figure 9. Realize gain comparisons.

3.3. Comparison with Other Works

Our work aims to align the main beam pattern at the concerned frequency to the broadside direction after decoupling. The simulated and measured results have validated this design. Thus, we compare our work with other decoupling methods where the edge-to-edge distance is approximately (a little less or more than) $0.05 \lambda_0$. The corresponding comparisons are listed in Table 2. The works in References [9,20] presented in Section 1 are not shown here. Due to Reference [9], the author only showed one pattern that was not tilted, while the asymmetrical feeding structure in Reference [20] makes the pattern essentially tilt.

Table 2. Comparisons with other works.

Literature	Placement Orientation	Decoupling Technique	Center Frequency	Edge-to-Edge Spacing	Tilt
[3]	E-plane	Dielectric Block	10.00 GHz	$0.027\lambda_0$	$\sim 10^\circ$
[10]	H-plane	Three Interdigital Lines	5.80 GHz	$0.07\lambda_0$	$\sim 30^\circ$
[11]	E-plane	Meander-line Slots	5.00 GHz	$0.06\lambda_g$	$\sim 30^\circ$
[13]	E-plane	Ground Slot	5.80 GHz	$0.031\lambda_0$	$\sim 45^\circ$
[14]	E-plane	Slotted Ground	4.00 GHz	$0.037\lambda_0$	$\sim 30^\circ$
[15]	H-plane	Metal Stub & Slotted Ground	5.50 GHz	$0.018\lambda_0$	$\sim 25^\circ$
[16]	H-plane	Asymmetrical Coplanar Strip Wall	5.80 GHz	$0.03\lambda_0$	$\sim 30^\circ$
[18]	H-plane	Half-wave Microstrip Line & Shorting Pin	3.16 GHz	$0.027\lambda_0$	$\sim 30^\circ$
Our Work	H-plane	T-type Metal Wall	5.80 GHz	$0.05\lambda_0$	0°

The works in References [3,16] adopted the high-profile techniques, while the remainder used the planar decoupling structure. However, all the maximum radiation directions deviate from the broadside direction to the fixed angles, regardless of the patch arrangement along the E- or H-plane direction. This deviation means that the broadside radiation will be reduced when they form the array. Therefore, this common problem prompts us to investigate the pattern-corrected decoupling technique so that the proposed method has corrected the pattern to the broadside direction for the concerned frequency, where the simulated frequency of 5.80 GHz is shown.

3.4. Current Distribution Comparison

The current distribution is compared before and after using the proposed decoupling structure, as shown in Figure 10. Figure 10a indicates the current distribution of the no-decoupling structure, while Figure 10b shows the distribution after using the proposed technique. This means that the coupling is reduced significantly by the T-type metal wall, and the current concentrates on the vertical strip of the T-type metal.

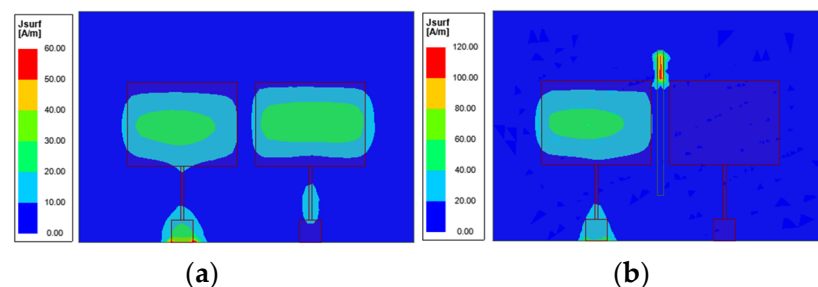


Figure 10. Current distributions before (a) and after (b) using the proposed structure.

4. Mechanism and Equivalent Circuit Analyses

As shown in Figure 10b, the current concentrates on the vertical wall's position, indicating that the corresponding surface current, surface wave, and radiated wave, will be induced in this proposed structure. The mixture of these three influencing factors will form a specific current distribution at the desired frequency on the T-type metal. Figure 11 shows the current distribution of the desired 5.80 GHz of the proposed structure. This indicates that a resonant structure is formed if the dimensions of the vertical and parallel strips are set properly.

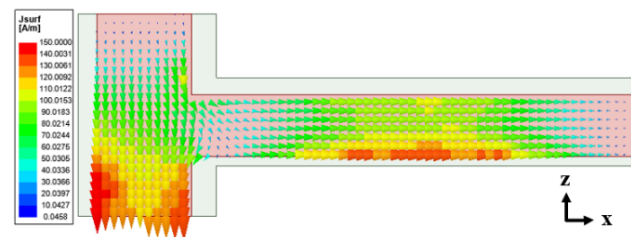


Figure 11. Resonator of the T-type metal.

The formed resonator by the induced current makes the vertical wall a bandstop filter, thus preventing the current from flowing to the other antenna. This can easily be explained by the corresponding equivalent circuit model, as shown in Figure 12. Here, the conventional patch antenna is equivalent to the parallel RLC circuit and they are placed symmetrically on the T-type vertical wall, while the corresponding parallel RLC circuit also indicates the T-type vertical wall.

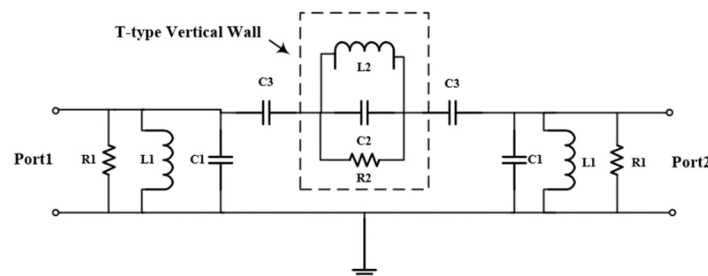


Figure 12. The equivalent circuit for the proposed structure.

When the patch is excited, there is a voltage difference between the patch and the T-type vertical wall, which means that capacitive coupling exists. Thus, we use the capacitance $C3$ to indicate this coupling. If the vertical wall induces the coupling, the symmetrical T-type metals form the corresponding resonance, which causes the parallel resonant circuit form, as indicated by $R2$, $L2$, and $C2$, respectively.

Subsequently, the corresponding values for these components are extracted using the ADS 2020 and listed in Table 3. The responding comparison between the simulated results by HFSS and ADS software are shown in Figure 13. From this, we know that the S_{11} and S_{21} agree well with each other, thus validating the equivalent circuit.

Table 3. Values of the components.

Component	R1	L1	C1	R2	L2	C2	C3
Value	60 Ω	0.07 nH	10.8 pF	620 Ω	0.29 nH	2.6 pF	40 pF

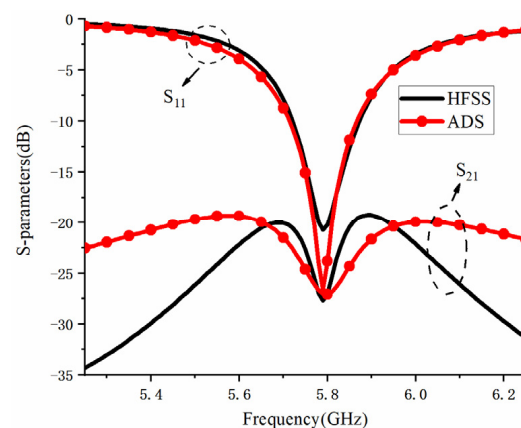


Figure 13. Comparison between the HFSS and ADS results.

5. Conclusions

Depending on the miniaturization development trend of 5G/6G, a pattern-corrected decoupling technique was proposed for the H-plane parallel patch antenna with a spacing of about $\lambda_0/20$. The decoupling structure consisted of a single substrate and two symmetrical T-type metals etched on it where the vertical strip must connect to the ground plane of the patch antenna. This structure will partly prevent the radiated wave, surface wave, and surface current from different parts of the fed antenna. Properly designing the proposed wall to form a resonator reduces the mutual coupling to lower than -20 dB in the desired bandwidth, and the pattern at the concerned frequency is corrected to the broadside direction.

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References

1. Li, M.; Zhong, B.G.; Cheung, S.W. Isolation Enhancement for MIMO Patch Antennas Using Near-Field Resonators as Coupling-Mode Transducers. *IEEE Trans. Antennas Propag.* **2019**, *67*, 755–764. [\[CrossRef\]](#)
2. Niu, Z.; Zhang, H.; Chen, Q.; Zhong, T. Isolation Enhancement in Closely Coupled Dual-Band MIMO Patch Antennas. *IEEE Antennas Wirel. Propag. Lett.* **2019**, *18*, 1686–1690. [\[CrossRef\]](#)
3. Li, M.; Jamal, M.Y.; Jiang, L.; Yeung, K.L. Isolation Enhancement for MIMO Patch Antennas Sharing a Common Thick Substrate: Using a Dielectric Block to Control Space-Wave Coupling to Cancel Surface-Wave Coupling. *IEEE Trans. Antennas Propag.* **2021**, *69*, 1853–1863. [\[CrossRef\]](#)
4. Qamar, Z.; Naeem, U.; Khan, S.A.; Chongcheawchamnan, M.; Shafique, M.F. Mutual Coupling Reduction for High-Performance Densely Packed Patch Antenna Arrays on Finite Substrate. *IEEE Trans. Antennas Propag.* **2016**, *64*, 1653–1660. [\[CrossRef\]](#)
5. Mohamadzade, B.; Afsahi, M. Mutual coupling reduction and gain enhancement in patch array antenna using a planar compact electromagnetic bandgap structure. *IET Microw. Antennas Propag.* **2017**, *11*, 1719–1725. [\[CrossRef\]](#)
6. Yang, X.M.; Liu, X.G.; Zhou, X.Y.; Cui, T.J. Reduction of Mutual Coupling between Closely Packed Patch Antennas Using Waveguided Metamaterials. *IEEE Antennas Wirel. Propag. Lett.* **2012**, *11*, 389–391. [\[CrossRef\]](#)

7. Alsath, M.G.N.; Kanagasabai, M.; Balasubramanian, B. Implementation of Slotted Meander-Line Resonators for Isolation Enhancement in Microstrip Patch Antenna Arrays. *IEEE Antennas Wirel. Propag. Lett.* **2013**, *12*, 15–18. [\[CrossRef\]](#)
8. Yang, X.; Liu, Y.; Xu, Y.-X.; Gong, S.-X. Isolation Enhancement in Patch Antenna Array with Fractal UC-EBG Structure and Cross Slot. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 2175–2178. [\[CrossRef\]](#)
9. Vishvakshnan, K.S.; Mithra, K.; Kalaiarasan, R.; Raj, K.S. Mutual Coupling Reduction in Microstrip Patch Antenna Arrays Using Parallel Coupled-Line Resonators. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 2146–2149. [\[CrossRef\]](#)
10. Qi, H.; Yin, X.; Liu, L.; Rong, Y.; Qian, H. Improving Isolation between Closely Spaced Patch Antennas Using Interdigital Lines. *IEEE Antennas Wirel. Propag. Lett.* **2016**, *15*, 286–289. [\[CrossRef\]](#)
11. Hwangbo, S.; Yang, H.Y.; Yoon, Y.-K. Mutual Coupling Reduction Using Micromachined Complementary Meander-Line Slots for a Patch Array Antenna. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 1667–1670. [\[CrossRef\]](#)
12. Wei, K.; Li, J.-Y.; Wang, L.; Xing, Z.-J.; Xu, R. Mutual Coupling Reduction by Novel Fractal Defected Ground Structure Bandgap Filter. *IEEE Trans. Antennas Propag.* **2016**, *64*, 4328–4335. [\[CrossRef\]](#)
13. OuYang, J.; Yang, F.; Wang, Z.M. Reducing Mutual Coupling of Closely Spaced Microstrip MIMO Antennas for WLAN Application. *IEEE Antennas Wirel. Propag. Lett.* **2011**, *10*, 310–313. [\[CrossRef\]](#)
14. Niu, Z.-C.; Zhang, H.; Chen, Q.; Zhang, T. Isolation Enhancement for 1×3 Closely Spaced E-Plane Patch Antenna Array Using Defect Ground Structure and Metal-Vias. *IEEE Access* **2019**, *7*, 119375–119383. [\[CrossRef\]](#)
15. Ghannad, A.A.; Khalily, M.; Xiao, P.; Tafazolli, R.; Kishk, A.A. Enhanced Matching and Vialless Decoupling of Nearby Patch Antennas for MIMO System. *IEEE Antennas Wirel. Propag. Lett.* **2019**, *18*, 1066–1070. [\[CrossRef\]](#)
16. Qi, H.; Liu, L.; Yin, X.; Zhao, H.; Kulesza, W.J. Mutual Coupling Suppression between Two Closely Spaced Microstrip Antennas with an Asymmetrical Coplanar Strip Wall. *IEEE Antennas Wirel. Propag. Lett.* **2016**, *15*, 191–194. [\[CrossRef\]](#)
17. Li, M.; Tian, S.; Tang, M.-C.; Zhu, L. A Compact Low-Profile Hybrid-Mode Patch Antenna with Intrinsically Combined Self-Decoupling and Filtering Properties. *IEEE Trans. Antennas Propag.* **2022**, *70*, 1511–1516. [\[CrossRef\]](#)
18. Pei, T.; Zhu, L.; Wang, J.; Wu, W. A Low-Profile Decoupling Structure for Mutual Coupling Suppression in MIMO Patch Antenna. *IEEE Trans. Antennas Propag.* **2021**, *69*, 6145–6153. [\[CrossRef\]](#)
19. Fang, Y.; Tang, M.; Zhang, Y.P. A Decoupling Structure for Mutual Coupling Suppression in Stacked Microstrip Patch Antenna Array. *IEEE Antennas Wirel. Propag. Lett.* **2022**, *21*, 1110–1114. [\[CrossRef\]](#)
20. Sun, X.-B.; Cao, M.-Y. Low mutual coupling antenna array for WLAN application. *Electron. Lett.* **2017**, *53*, 368–370. [\[CrossRef\]](#)
21. Lin, H.; Chen, Q.; Ji, Y.; Yang, X.; Wang, J.; Ge, L. Weak-Field-Based Self-Decoupling Patch Antennas. *IEEE Trans. Antennas Propag.* **2020**, *68*, 4208–4217. [\[CrossRef\]](#)
22. Lai, Q.-X.; Pan, Y.-M.; Zheng, S.-Y.; Yang, W.-J. Mutual Coupling Reduction in MIMO Microstrip Patch Array Using TM_{10} and TM_{02} Modes. *IEEE Trans. Antennas Propag.* **2021**, *69*, 7562–7571. [\[CrossRef\]](#)
23. Wang, Y.-Y.; Zhang, S.-F.; Yan, Y.-T.; Yu, X.-H.; Kishk, A.A. Vertical-Wall between Tightly Spaced Patch Antennas for Decoupling and Radiation Pattern Correction. In Proceedings of the IEEE International Symposium on Antennas and Propagation and USNC-URSI Radia Science Meeting (APS/URSI), Singapore, 4–10 December 2021.