Multi-Mode High-Gain Antenna Array Loaded With High Impedance Surface

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ABSTRACT A novel and simple broadband antenna array loaded with high impedance surface is proposed in this letter. The unit cell is composed of a main radiating patch and a pair of EBG arrays placed symmetrically at the two radiating edges of the main radiating patch. The main radiating patch is responsible for the original TM10 mode while the electromagnetic bandgap (EBG) arrays is for another resonant mode characterized as quasi-TM20 mode. Thus, wideband performance is obtained due to the combination of the two generated resonant modes. And on this basis, by adding symmetrical mushroom structures at the other two edges of the main radiating patch, the impedance bandwidth and sidelobe suppression are improved. The current distributions on the all metal patches are almost uniform, therefore high gains can be obtained during the whole operating bandwidth. The antenna array is formed by 4 × 4 unit cells and the prototype is fabricated to validate the design. The measured results show that the impedance bandwidth is broadened from 11.1 to 15.6 GHz with the peak-gain reaching as high as 18.8dBi. Besides, the proposed antenna is easy fabrication with low profile which provides great convenience in the actual beam and point-to-point communication applications.

INDEX TERMS Broadband, high gain, antenna array, high impedance surface.

I. INTRODUCTION

With the great development of wireless communication, the wideband and high-gain antennas are in great demand [1]. The conventional microstrip antenna has drawbacks of low gain and narrow bandwidth which limits the actual application. Antenna array can improve the performance of the antenna to satisfy the specific operating requirements. The researcher have presented various methods to broaden the bandwidth of microstrip antennas, such as increasing substrate thickness [2], embedding slots in the patch [3], adding aperture coupled feeding network [4], applying parasitic strips [5], and stacking patches on multilayered substrate [6]. The methods are effective and greatly improve the bandwidth of the microstrip antennas. What’s more, some researchers have improved the gain of the antenna by dielectric resonator antenna [7]–[9]. However, some other challenges such as gain improvement and planar structure are brought.

For the past few years, metamaterial [10]–[12] have drawn many attentions due to the advantages of excellent performance. With an increasingly extensive study and utilization, a variety of metamaterial structures with good characteristics are proposed, such as frequency selective surface (FSS) [13], electromagnetic bandgap (EBG) [14], [15], and metasurface (MS) [16]–[19]. The combination of metamaterial and traditional antenna called novel antennas and they have great advantages in gain improvement, high directivity, and antenna miniaturization. EBG structures provide possible solutions to the key technical problems for antenna design owing to their two unique characteristics of frequency and phase band gaps. Therefore, it has great academic value and application prospects to study new EBG structures and explore new areas of EBG structure in antenna design. Mushroom-like EBG designed in [20], [21] is a two-dimensional planar structure combined with metal and substrate. Compared with traditional EBG structure, the structure has infinite external reactance characteristic in the operating bands called high impedance surface (HIS) [22]–[24].
In [25], a broadband mushroom antenna with an impedance bandwidth of 15.8% is obtained due to the dual resonance modes. A dual-band antenna for wireless local area network applications is achieved by loading mushroom-like rectangular patches [26]. A high-impedance periodic structure (HIPS) is applied to improve radiation pattern of the antenna element in an array with a high-impedance is analyzed [27]. In [28], a low profile (0.019λ), lightweight, linearly polarized antenna has been designed for 0.9 GHz applications using a double layered via-less high impedance surface. Most of the antennas mentioned above are designed on multilayered substrate. Besides, we are able to obtain wider bandwidth for our antenna configuration. The emphasis of this article is on the additional resonances of the radiating structure caused by surface waves propagating on the high-impedance surface [29]. It is shown that such resonances can be favorably used for broadening the bandwidth of the antenna. The antennas mentioned above have obtained good results in broadening the bandwidth and improving the gain. However, it is still a challenge to obtain broad bandwidth and high gain at the same time.

In this article, a multi-mode high-Gain antenna array loaded with high impedance surface is designed based on the previous work. Both the conventional TM\textsubscript{10} mode and a new quasi-TM\textsubscript{20} mode are obtained to obtain broad bandwidth. On this basis, by adding symmetrical mushroom structure at the other two edges of the main radiating patch, the impedance bandwidth and sidelobe suppression are improved. Based on the feeding structure, a 4 × 4 antenna array with high impedance surface is designed and fabricated.

The measured results indicate that the enhanced impedance bandwidth is from 11.1 to 15.6 GHz. Meanwhile, peak-gain can reach as high as 18.8dBi. The proposed antenna maintains the advantages of wide bandwidth, easy fabrication, flat and high gains which provides great convenience in the actual beam and point-to-point communication applications. The paper is divided into four parts. In Section II, the antenna design and comparison with conventional patch antenna are given. And then, the experimental results and discussion are presented in section III. Finally, the work is concluded in the last part.

### II. ANTENNA DESIGN

#### A. ANTENNA GEOMETRY

The configuration of the proposed antenna unit cell is given in Figure 1. It can be clearly seen that the unit cell is composed of a main radiating patch with size of L\textsubscript{p} × W\textsubscript{p}, a pair of main EBG arrays placed symmetrically at the two radiating edges of the main radiating patch, assisted mushroom structures placed along the other two edges, and a L × W metal ground plane. The main EBG arrays include three mushroom units in the same size and one unit consists of a square patch with periodicity L\textsubscript{a} and a center-placed circle with radius R\textsubscript{2}. The distance between EBG units is W\textsubscript{1}. The assisted mushroom-EBG structure is two square patches with periodicity L\textsubscript{b} and the distance between the main radiating patch is g. The antenna element is designed on a substrate with permittivity of 2.2, loss tangent of 0.0009, and thickness of 1.524 mm. Besides, the coaxial feeding method is used. The optimized dimensions of the proposed antenna are listed in Table 1.

| TABLE 1. Units for magnetic properties (unit:mm). |
|-----------------|-----------------|-----------------|-----------------|
| L\textsubscript{p} | W\textsubscript{p} | L\textsubscript{a} | L\textsubscript{b} |
| 32              | 25              | 5.8             | 4              |
| L\textsubscript{a} | W\textsubscript{a} | W\textsubscript{2} | L\textsubscript{b} |
| 7.1             | 0.8             | 1.9             | 2.4            |
| W\textsubscript{1} | R\textsubscript{2} | R\textsubscript{3} | H              |
| 4.4             | 0.65            | 0.3             | 1.524          |

**FIGURE 1.** Side and Top view of the unit cell of the proposed antenna.

**FIGURE 2.** Evolution of the proposed antenna unit cell.

#### B. COMPARISON WITH CONVENTIONAL PATCH ANTENNA

For better understanding the antenna design and mechanism, the evolution of the proposed patch antenna element is given in Figure 2. The conventional patch antenna called ant.1. By adding two main EBG arrays symmetrically at the two radiating edges of the main radiating patch, ant.2 is obtained. And a new resonant frequency is excited due to the loaded EBG structures. To improve the impedance bandwidth and sidelobe suppression, ant.3 is designed by employing the assisted mushroom-EBG structure. The simulated $|S_{11}|$ of the three antennas are shown in Figure 3. We can see that another resonant frequency is excited due to the loaded EBG structures and the bandwidth is broadens from 11.2 to 15 GHz. And the mushroom structures improve the impedance matching.

To show the impact of the loaded EBG structures more intuitively, the electric field distributions of the antenna element at two resonant modes are analyzed. Figure 4 show the
FIGURE 3. Comparison of simulated $S_{11}$ of the different patch antennas.

FIGURE 4. TM$_{10}$ mode at resonant frequency 12.2 GHz. (a) Simulated current distribution. (b) Simulated electric field distribution. (c) Sketch of the operation mechanism.

Simulated current distribution and electric field distribution at 12.2 GHz. It can be clearly seen that the electric field distribution is the same as TM$_{10}$ mode which like a conventional patch antenna. The reason is that in the lower operation bands, the main radiating patch plays the most important part in radiating energy. So that only little energy is transmitted to the mushroom-type structure which can be neglected. Similarly, the simulated current distribution and electric field distribution at the new resonant frequency 14.3 GHz is given in Figure 5. We can see that the electric field distribution like TM$_{20}$ mode and we name it quasi-TM$_{20}$ mode. The difference is that at the upper frequency band, more energy can be coupled to the EBG structure compared with lower frequency band. This means energy can be radiated through EBG structures.

A transmission-line model is employed to determine the resonant frequency for the quasi-TM$_{20}$ mode in theory. The extended length can be approximated to that of the corresponding entire rectangular patch, as given in [30]. The resonant frequency for the quasi TM$_{20}$ mode can be calculated approximately by

$$\beta_{mp}N/2 + 2\beta_e\Delta L = \pi$$  \hspace{1cm} (1)

And $\Delta L$ is the extended length, $\beta_e$ represents the propagation constant in the extended region, $p$ is EBG unit period, $N$ (here $N = 3$) is the number of EBG units. The $\beta_e$ and $\Delta L$ can be calculated by equation (2) and equation (3) respectively.

$$\beta_e = k_0\sqrt{\varepsilon_{\text{eff}} = \frac{2\pi f}{c}} \sqrt{\varepsilon_{\text{eff}}}$$ \hspace{1cm} (2)

$$\Delta L = 0.412H (\varepsilon_{\text{eff}} + 0.3) (W_e/\epsilon_0 + 0.262)\left(\varepsilon_{\text{eff}} - 0.258\right)(W_e/H + 0.813)$$ \hspace{1cm} (3)

where $f$ represents the operating frequency, $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the substrate and $c$ is the free-space velocity of light, $k_0$ is the wavenumber in free space, $W_e$ is the width of the EBG structure.

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + \frac{H}{W_e}\right)^{-1}$$ \hspace{1cm} (4)

$$W_e = Np - W_1$$ \hspace{1cm} (5)

From formula (1), the resonant frequency for the quasi-TM$_{20}$ mode can be calculated as 15.3 GHz (where the corresponding $\beta_{mp}/\pi$ is 0.528). And the calculated results is slightly different from the simulated one of 14.3 GHz due to...
the main driven patch has an effect on the resonant frequency. For a conventional patch antenna, it is impossible to realize wide bandwidth through combining $TM_{10}$ mode and $TM_{20}$ mode because of the different resonant frequency. By adding symmetrical EBG structures to the patch, another resonant mode characterized as quasi-$TM_{20}$ mode can be obtained. And the resonant frequency of the quasi-$TM_{20}$ mode can be adjusted closely to that of the $TM_{10}$ mode by changing the parameters. At last, the impedance bandwidths is broadened by combining the two modes.

C. PARAMETER STUDY AND ANTENNA ARRAY

To choose the best parameters, we change one parameter at a time while keeping the other parameters unchanged. Some key parameters have great influence on the performance of the antenna. Through the changes of these parameters, we can seek a rule that will lay the foundation for the optimization and simplification of the antenna design in the next step. To better analyze the antenna, imaginary part of the input impedance is also given. The effects of the distance between the main radiating patch and mushroom-type structure $g$ on the antenna is given in Figure 6. The increasing of $g$ means EBG structure is away from the main radiation patch gradually. And the second resonance point disappears step by step which means the two resonant modes is away. Broadband operating bandwidth can be obtained by the combination of the two resonance modes, and $g = 0.3\text{mm}$ is chosen. Figure 7 shows the effects of $W_1$, and we can see that, the upper operating band became worse as the increasing of $W_1$ while the lower part nearly unchanged, which verity the EBG mainly affect the high operating band. At last, we choose $W_1 = 0.8\text{mm}$. To show the affection of the assisted mushroom structure on the proposed structure, the variation curve of the proposed antenna with increasing of $W_3$ is shown in Figure 8. It can be seen that the lower operating band became better with the increasing of $W_3$ while the upper nearly unchanged and $W_3 = 2.4\text{mm}$ is chosen. We can see that the adding symmetrical mushroom structures mainly adjust the impedance matching. Figure 9 shows the effects of radiation patch width $W_p$ on the antenna. With the increasing of $W_p$, the impedance matching is better although the impedance bandwidths became narrow. For balance, we choose $W_p = 4.4\text{mm}$.

On the basis of unit cell, a $4 \times 4$ antenna array is constructed. Figure 10(a) shows the configuration of the $4 \times 4$ antenna array loaded with high impedance surface. The antenna is fed by the one-to-sixteen power dividers and the feeding structure is shown in Figure 10(b). The feed network is designed on a FR4 substrate with permittivity of 4.4, loss tangent of 0.02, and thickness of 0.6 mm. The metal ground is placed above the substrate while the microstrip power-divider network is on the bottom. As shown in Figure 10(c), the stratified expansion structure is given in Figure 11 to
show the antenna array better. When the antenna array is constructed, there are two substrates.

**FIGURE 11.** Stratified expansion structure of the antenna array.

The upper substrate is radiation substrate with the radiation patch and EBG structure above while the metal ground below it. The lower substrate is feed network and the one-to-sixteen power divider is below the substrate. The sixteen metal probes are employed to connect the radiation patch and power divider. The whole size of the antenna array is $L_g = 72 \text{mm}$, $W_g = 64 \text{mm}$, $H_f = 0.6 \text{mm}$.

**FIGURE 12.** Photograph of the fabricated wideband slot antenna. (a) Top-view. (b) metal ground. (c) Back-view. (d) Measurement environment.

**III. EXPERIMENTAL RESULTS AND DISCUSSION**

To verify the design, the proposed antenna prototype is fabricated. Figure 12 shows the photograph of the proposed wideband slot antenna array. The antenna prototype was tested in a standard anechoic chamber and the $|S_{11}|$ of the antenna is measured with an AV 3672B vector network analyzer.

![Simulated and measured results of the antenna array.](image-url)

**FIGURE 13.** Simulated and measured results of the antenna array. (a) Reflection coefficient (b) Gain.

Figure 13 shows the simulated and measured reflection coefficients and broadside gains. We can see that the impedance bandwidth of the proposed antenna array is from 11.2 to 15.6 GHz (32.8%). The difference between the simulated and measured results is due to the dielectric loss and fabrication tolerance. Besides, the gain in the whole operating band is good which makes the antenna available for broad applications.

The far-field radiation patterns are also measured and are shown in Figure 14. It can be seen that good agreements are obtained between the simulated and measured results. At the four different frequency points during the operating band stable broadside radiation patterns can be observed. And the cross-polarization level is less than $-40 \text{ dB}$ in the E-plane, so we can’t see it in Figure 14 (a), (c), and (e). Meanwhile, in the H-plane, the measured cross polarization level is less than $-25 \text{ dB}$. Compared with traditional patch antennas, the beam width of the proposed antenna is narrower which leads to high gains. As shown in Figure 14(h), the quasi-TM20 mode at the higher frequency band (15 GHz) leads to the high side-lobe level (SLL). And the high SLL leads to the sharply decreased gains after 15GHz in Figure 12. The comparison of the proposed antenna with other antennas designed in the literatures is given in Table 2.
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show that the impedance bandwidth of the proposed antenna
surface is designed and fabricated. The measured results
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IV. CONCLUSION
In this letter, multi-mode high-gain antenna array loaded with high impedance surface is investigated. The antenna element is composed of a main radiating patch, a pair of main EBG arrays placed symmetrically at the two radiating edges of the main radiating patch, assisted mushroom structures placed along the other two edges, and a ground plane. Base on the feeding structure, a 4×4 antenna array with high impedance surface is designed and fabricated. The measured results show that the impedance bandwidth of the proposed antenna array is from 11.2 to 15.6 GHz (32.8%). And the proposed antenna exhibits high-gain in the operating band. In addition, the proposed antenna is simple structure, low profile, and easy fabrication which means a good candidate for the actual beam and point-to-point communication applications.

REFERENCES
[1] B.-Y. Duan, “Evolution and innovation of antenna systems for beyond 5G and 6G,” Frontiers Inf. Technol. Electron. Eng., vol. 21, no. 1, pp. 1–3, Jan. 2020.
[2] F.-W. Wang, Y. Ren, and K. Li, “An absorbing/ transmissive radome based on tantalum nitride,” in Proc. Cross Strait Quad-Regional Sci. Wireless Technol. Conf., Jul. 2019, pp. 1–3.
[3] P. Juyal and L. Shafai, “Gain enhancement in circular microstrip antenna via linear superposition of higher zeros,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 896–899, 2017.
[4] P. Xie, G. Wang, H. Li, and X. Gao, “A novel methodology for gain enhancement of the Fabry–Pérot antenna,” IEEE Access, vol. 7, pp. 176170–176176, 2019.
[5] W. J. Yang, Y. M. Pan, and S. Y. Zheng, “A low-profile wideband circularly polarized crossed-dipole antenna with wide axial-ratio and gain beamwidths,” IEEE Trans. Antennas Propag., vol. 66, no. 7, pp. 3346–3353, Jul. 2018.
[6] V. P. Sarin, M. S. Nishamol, D. Tony, C. K. Aanandan, P. Mohanam, and K. Vasudevan, “A wideband stacked offset microstrip antenna with improved gain and low cross polarization,” IEEE Trans. Antennas Propag., vol. 59, no. 4, pp. 1376–1379, Apr. 2011.
[7] A. K. Pandey, M. Chauhan, V. K. Killamsetty, and B. Mukherjee, “High-gain compact rectangular dielectric resonator antenna using metamaterial as superstrate,” Int. J. RF Microw. Comput.-Aided Eng., vol. 29, no. 12, pp. 1–10, Dec. 2019.
[8] M. Sinha, V. Killamsetty, and B. Mukherjee, “Near field analysis of RDRA loaded with split ring resonators superstrate,” Microw. Opt. Technol. Lett., vol. 60, no. 2, pp. 472–478, Feb. 2018.
[9] V. R. Kaushik and R. K. Gangwar, “Metal loaded low profile and compact dielectric resonator antenna for WiMAX/WLAN applications,” J. Adv. Res. Appl. Sci., vol. 4, no. 4, pp. 34–37, 2017.
[10] Y. B. Li, B. G. Cai, Q. Cheng, and T. J. Cui, “Textile antenna with EBG structure for 5G applications,” IEEE Access, vol. 7, pp. 1561–1564, 2019.
[11] C. Tian, Y.-C. Jiao, G. Zhao, and H. Wang, “A wideband transmittarray using triple-layer elements combined with cross slots and double square rings,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1561–1564, 2017.
[12] W. Ji, T. Cai, G. Wang, Y. Sun, H. Li, C. Wang, C. Zhang, and Q. Zhang, “Three-dimensional ultra-broadband absorber based on novel zigzag-shaped structure,” Opt. Express, vol. 27, no. 22, p. 32835, Oct. 2019.
[13] M. Borhani Kakhki, A. Dadgarpour, A.-R. Sebak, and T. A. Denidni, “Twenty-eight-gigahertz beam-switching ridge gap dielectric resonator antenna based on FSS for 5G applications,” IET Microw., Antennas Propag., vol. 14, no. 5, pp. 397–401, Apr. 2020.
[14] J. Tak, Y. Hong, and J. Choi, “Textile antenna with EBG structure for body surface wave enhancement,” Electron. Lett., vol. 51, no. 15, pp. 1131–1132, Jul. 2015.
[15] H. N. Chen, J.-M. Song, and J.-D. Park, “A compact circularly polarized MIMO dielectric resonator antenna over electromagnetic band-gap surface for 5G applications,” IEEE Access, vol. 7, pp. 140889–140898, 2019.
[16] H. Bai, G.-M. Wang, and T. Wu, “High-gain wideband metasurface antenna with low profile,” IEEE Access, vol. 7, pp. 177266–177273, 2019.
[17] H.-P. Li, G.-M. Wang, X.-J. Gao, J.-G. Liang, and H.-S. Hou, “A novel metasurface for dual-mode and dual-band flat high-gain antenna application,” IEEE Trans. Antennas Propag., vol. 66, no. 7, pp. 3706–3711, Jul. 2018.
[18] C. Zhang, G. Wang, H. Xu, X. Zhang, and H. Li, “Helicity–dependent multifunctional metasurfaces for full-space wave control,” Adv. Opt. Mater., vol. 8, no. 8, Apr. 2020, Art. no. 1901719.
[19] M. Farahani, J. Pourahmadazar, M. Akbari, M. Nedi, A. R. Sebak, and T. A. Denidni, “Mutual coupling reduction in millimeter-wave MIMO antenna array using a metamaterial polarization-rotator wall,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2324–2327, 2017.
[20] K. Konstantinidis, A. P. Feresidis, and P. S. Hall, “Broadband sub-wavelength profile high-gain antennas based on multi-layer metasurfaces,” IEEE Trans. Antennas Propag., vol. 63, no. 1, pp. 423–427, Jan. 2015.

IV. CONCLUSION

TABLE 2. The comparisons with reference antenna.

| Reference Antennas | Dimensions (λ0) | Bandwidth (GHz) | Center Frequency (GHz) | Peak Gain (dBi) |
|--------------------|----------------|----------------|------------------------|----------------|
| [21]               | 1.81×1.81×0.05 | 37.3          | 5.8                    | 13             |
| [23]               | 0.88×1.04×0.01 | 20            | 2.4                    | 5.1            |
| [25]               | 1.5×1.5×0.05   | 15.8          | 9                      | 14.1           |
| [27]               | 4.1×0.4×0.02   | 20            | 3.5                    | 15.7           |
| This work          | 3.2×2.8×0.09   | 32.8          | 13.4                   | 18.8           |
[21] Q. Zheng, C. Guo, G. A. E. Vandenbosch, and J. Ding, “Low-profile circularly polarized array with gain enhancement and RCS reduction using polarization conversion EBG structures,” IEEE Trans. Antennas Propag., vol. 68, no. 3, pp. 2440–2445, Mar. 2020.

[22] X. Chen, L. Li, C. H. Liang, Z. J. Su, and C. Zhu, “Dual-band high impedance surface with mushroom-type cells loaded by symmetric meandered slots,” IEEE Trans. Antennas Propag., vol. 60, no. 10, pp. 4677–4687, Oct. 2012.

[23] D. Cure, T. M. Weller, and F. A. Miranda, “Study of a low-profile 2.4-GHz planar dipole antenna using a high-impedance surface with 1-D varactor tuning,” IEEE Trans. Antennas Propag., vol. 61, no. 2, pp. 506–515, Feb. 2013.

[24] D. Wen, Y. Hao, M. O. Munoz, H. Wang, and H. Zhou, “A compact and low-profile MIMO antenna using a miniature circular high-impedance surface for wearable applications,” IEEE Trans. Antennas Propag., vol. 66, no. 1, pp. 96–104, Jan. 2018.

[25] C. H. Liang, Z. J. Su, C. Zhu, and L. J. Li, “High-gain patch antenna based on cylindrically projected EBG planes,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 12, pp. 2374–2378, Dec. 2018.

[26] Z. Wu, L. Li, X. Chen, and K. Li, “Dual-band antenna integrating with rectangular mushroom-like superstrate for WLAN applications,” IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1269–1272, 2016.

[27] G. Yang, J. Li, R. Xu, Y. Ma, and Y. Qi, “Improving the performance of wide-angle scanning array antenna with a high-impedance periodic structure,” IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1819–1822, 2016.

[28] G. Gupta and A. R. Harish, “Antenna on cavity backed high impedance surface,” IEEE Trans. Antennas Propag., vol. 65, no. 1, pp. 374–379, Jan. 2017.

[29] A. O. Karilainen, J. Vehmas, O. Luukkonen, and S. A. Tretyakov, “High-impedance-surface-based antenna with two orthogonal radiating modes,” IEEE Antennas Wireless Propag. Lett., vol. 10, pp. 247–250, 2011.

[30] Y. Cao, Y. Cai, W. Cao, B. Xi, Z. Qian, T. Wu, and L. Zhu, “Broadband and high-gain microstrip patch antenna loaded with parasitic mushroom-type structure,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 7, pp. 1405–1409, Jul. 2019.

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