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A Gain-Enhanced Patch Antenna With a Periodic Microstrip Rampart Line

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ABSTRACT In this paper, a gain-enhanced patch antenna with a periodic microstrip rampart line is proposed. The periodic microstrip rampart line can modify the effective dielectric constant of the dielectric plate, and help to improve the gain of the traditional microstrip patch antenna. Based on the antenna design principle, a formula for calculating the gain-enhanced frequency point is proposed. A proposed high gain microstrip antenna is designed, fabricated and tested. The experimental results demonstrate that the gain of the proposed antenna reaches 10.0 dBi, which is 2.55 dB or 79.9% higher than that of the traditional patch antenna at the same operating frequency of 5.8 GHz. The measured and simulated results show a high consistency.

INDEX TERMS Gain-enhanced, patch antenna, leaky wave structure.

I. INTRODUCTION

THE MICROSTRIP patch antenna was proposed in the 1950s [1]. It has been then widely studied and developed. In the past decades, extensive research has been carried out to widen its operating bandwidth in impedance [2], [3]. With the growth of the communication distance, the gain of the traditional patch antennas cannot meet the actual needs in some cases [4], [5]. Therefore, improving the gain of traditional patch antennas is crucial. The high-gain antenna could be used in mid-range or high-data-rate communications for compensation of propagation loss.

Several methods have been proposed to improve the gain of microstrip antennas. For instance, the method in [6]–[9] consists in forming an antenna array. However, this may increase the design and manufacturing complexity. A substrate with a lower dielectric constant is used in [10], [11] to increase the gain. However, this requires a larger volume or higher profile. Parasitic radiation elements in stacked or planar structures are used in [12]–[14]. However, these antennas usually have a high profile or low aperture efficiency. The parallel inductive loading technology was also proposed [15], [16]. It consists in expanding the overall chip size at resonance. It is shown in [15] that the radiation gain increases with the expansion of the radiation area by loading the short pin. Another technology is developed in the high-mode operation of the patch antenna, due to the fact that the electrical size of the patch is much larger than that of the first mode [17]–[19]. However, the corresponding sidelobe level is high. The metasurface-based patch antenna achieves a high gain or wideband by manipulating the electromagnetic waves [20], [21]. This method consists in combining the metasurfaces (MSs) with the patch.

The microstrip leaky-wave antenna (MLWA) is a type of traveling-wave antenna [22] which is widely used in planar integrated communication systems due to its beam-scanning characteristics and high directivity [23]. An offset periodic structure loaded in a traditional microstrip antenna was presented in [24]. A patch antenna based on the periodic leaky-wave structure was also proposed in [25]. It has the multi frequency characteristics of the traditional patch antenna.

This paper proposes a gain-enhanced patch antenna with a periodic microstrip rampart line. That is a novel method designed to effectively improve the gain of the traditional microstrip patch antenna. The periodic microstrip rampart

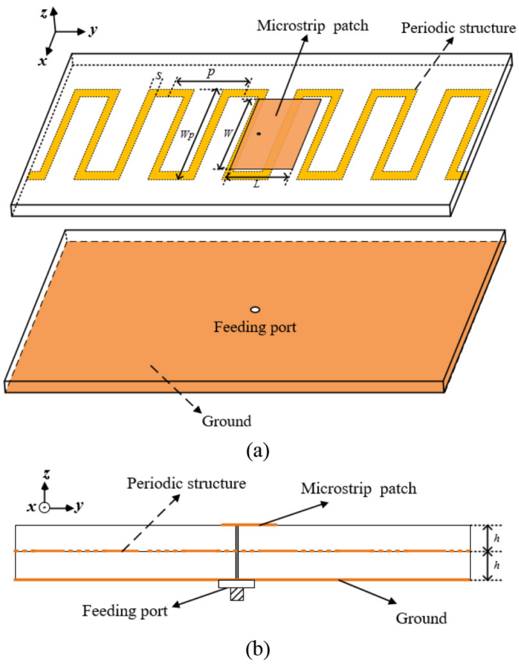


FIGURE 1. Layout of the gain-enhanced patch antenna with a periodic microstrip rampart line. (a) The 3-D decomposition figure (b) The Side view.

line can modify the effective dielectric constant of the dielectric plate, and affect the electric field distribution on the rectangular patch. It can help to expand the antenna radiation aperture, which leads to a gain increase. This paper also derives a formula allowing to calculate the gain-enhanced frequency point of the antenna, based on the principle of the microstrip patch antenna. A proposed high gain antenna and a traditional microstrip patch antenna are designed, built and tested. The measured *S*-parameter (S_{11}), radiation patterns and gains of the proposed antenna are also measured.

II. DESIGN DESCRIPTION

A novel design method is proposed to improve the patch antenna gain, by embedding periodic leaky-wave structure in the dielectric layer of the traditional patch antenna, as shown in Fig. 1. The top layer is a rectangular patch consistent with the traditional rectangular patch antenna, the middle layer is a periodic microstrip rampart line which is a typical leaky wave structure, and the bottom layer is a complete ground plane. The dielectric plate has a double-layer stacked structure, consisting of the same material and thickness. The periodic leaky wave structure is perpendicular to the two radiating edges.

When the feed connector feeds the top rectangular patch, the energy of the metal radiator is coupled to the periodic structure, which will perform in the leaky mode. Several order harmonics of periodic structure are excited, resulting in antenna propagation constant changes. The equivalent permittivity of the substrate changes with the different harmonics, which introduces some new resonant frequency [25]. Some of the frequencies are higher than the original frequency f_0, while the size of the leaky wave structure can be adjusted in order to change the propagation constant of the antenna. It can then adjust the equivalent permittivity corresponding to the new frequency point to a suitable value, until the frequency point is moved back to 5.8 GHz. Simultaneously, the introduced structure increases the effective radiation aperture of the antenna and improves its gain.

According to [15], the directivity of the conventional patch antenna operating in TM_{010} mode can be determined by referring to the patch aspect ratio *W/L*, the substrate height h/λ_0 and ε_{eff}. This can be simplified by a function F as:

$$D_{t0} = F\left(\frac{W}{L}, \frac{h}{\lambda_0}, \varepsilon_{eff}\right), \quad (1)$$

It can be observed from equation (1) that the antenna gain is positively correlated with the radiation aperture and equivalent permittivity. As the periodic leaky-wave structure is embedded, the radiation aperture and equivalent permittivity are changed, which affects the electric field distribution leading to a gain increase.

When the proposed antenna works, its propagation constant changes resulting in the dielectric plate anisotropy and the equivalent permittivity change [24]. The relationship between the two is given by:

$$\frac{\beta_z}{k_0} = \sqrt{\varepsilon_{eff}}, \quad (2)$$

where β_z is the fundamental harmonic phase constant of the periodic leaky wave structure.

According to Floquet's theorem, the electromagnetic wave that is radiated by the periodic leaky wave structure is composed of innumerable spatial harmonics and normalized phase constant:

$$\frac{\beta_{z,n}}{k_0} = \frac{\beta_z + 2n\pi/p}{k_0} = \sqrt{\varepsilon_{eff,n}} + \frac{2n\pi}{pk_0}, n = 0, -1, -2, \ldots, \quad (3)$$

where n is the order of the spatial harmonics leaked by periodic leaky wave structures.

The equivalent permittivity of the proposed antenna can be determined by the phase constants of the embedded periodic structure. When the resonant frequency f_0 of the original rectangular patch is located in the $n = -2$ Floquet mode of the leaky-wave structure, the specific form of the formula slightly changes. The formula was revised after several data fitting procedures:

$$\varepsilon_{eff,-2} = \left(\frac{0.1018\beta_{z,-2} + 196.7}{k_0}\right)^2, \quad (4)$$

where $\varepsilon_{eff,-2}$ denotes the equivalent permittivity of the model, k_0 represents the free-space wavenumber at the resonance frequency f_0 of the original antenna and $\beta_{z,-2}$ refers to the $n = -2$ Floquet mode of an unnormalized phase constant in the leaky-wave operating band of the periodic leaky wave structure at f_0. The latter can be calculated using the macro cell method provided in [26]. The macro cell method

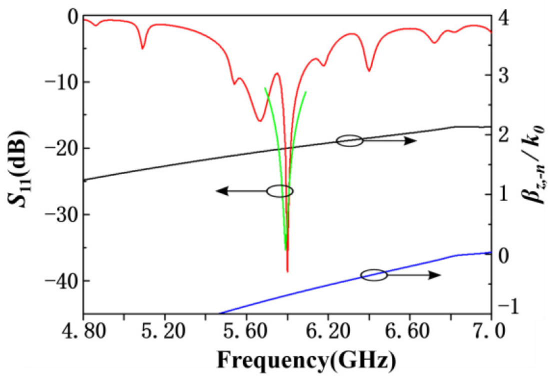


FIGURE 2. The simulated *S*-parameter (S_{11}) of the proposed antenna when the original rectangular patch f_0 is in the $n = -2$ mode operating band of the periodic leak-wave structure; $p = 21$ mm, $Wp = 23.2$ mm and $s = 2.2$mm.
— Calculated results at 5.79 GHz by using Eqs. (4).
— S_{11} value of the proposed antenna with a leak-wave structure by the Ansoft HFSS software; $f = 5.8$GHz.
— $\beta_{z,-1}$ of the periodic leak-wave structure calculated using the macro-cell method.
— $\beta_{z,-2}$ of the periodic leak-wave structure calculated using the macro-cell method.

is a fast approach for calculating the propagation constant of periodic leaky wave structures.

After calculating the equivalent permittivity of the model by (4), the resonant frequency point position can be calculated using the formula of the traditional patch antenna. It is important to mention that the design of high gain antennas can also be performed through the $n = -1$ Floquet mode. Both harmonics have a backward radiation ability due to their phase constants that are less than 0. However, the derived formula is not accurate enough as the $n = -2$ Floquet mode. Therefore, only the $n = -2$ Floquet mode is taken as example. The corresponding equivalent permittivity at high gain frequency can be calculated using equation (4), so that the high gain frequency point can also be determined. Fig. 2 presents the *S*-parameter (S_{11}) of the proposed antenna, the calculation results of the derived formula and the normalized phase constant of the periodic structure. It proves the feasibility of the proposed equations and antenna design method.

The equivalent dielectric constant of the proposed model is only related to the propagation constant of the embedded periodic leaky wave structure, and has no direct relationship with the periodic structure size. However, different shapes or sizes of leaky wave structures have their specific propagation constants, that can change the equivalent dielectric constant of the dielectric plate and move the frequency point of the proposed antenna. It can be seen in Fig. 3 that changing the size of the periodic leaky wave structure changes the propagation constant curve. When the normalized phase constant curve of the leaky wave structure moves from top to bottom, the specific value of $\beta_{z,-2}$ at f_0 decreases, and the resonant frequency of the proposed antenna gradually increases. Therefore, the corresponding gain curve of the antenna also moves to the high frequency. Similarly, changing the height of the substrate can result in the same frequency shift effect. The higher substrate results in the higher gain but poor matching. It can be observed from Fig. 4 that the change of the normalized phase constant

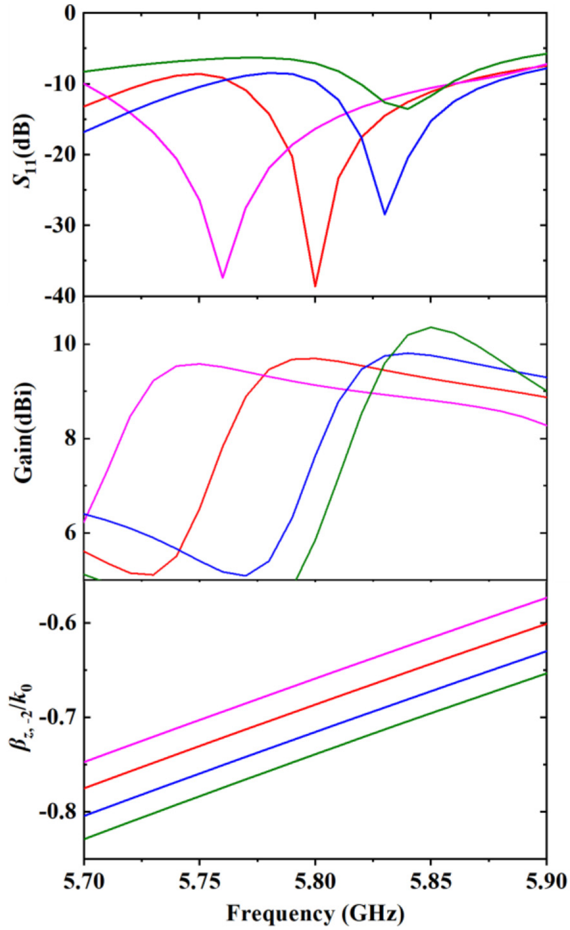


FIGURE 3. The simulated *S*-parameter (S_{11}) and gain of the proposed antenna in normal direction at 5.8 GHz, and $\beta_{z,-2}$ of the periodic structure with different sizes and $s = 2.2$mm.
— $p = 22.0$ mm, $Wp = 23.2$ mm, $h = 0.8$mm.
— $p = 21.0$ mm, $Wp = 23.2$ mm, $h = 0.8$mm.
— $p = 21.0$ mm, $Wp = 23.0$ mm, $h = 0.8$mm.
— $p = 21.0$ mm, $Wp = 23.2$ mm, $h = 1.6$mm.

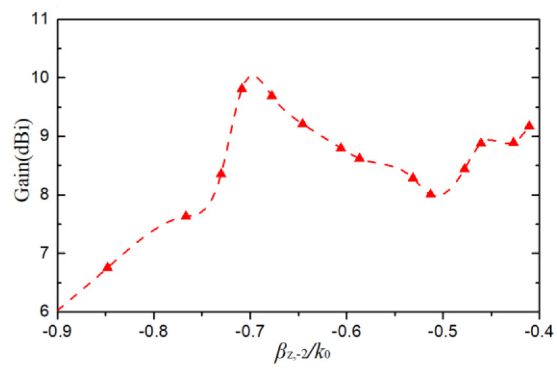
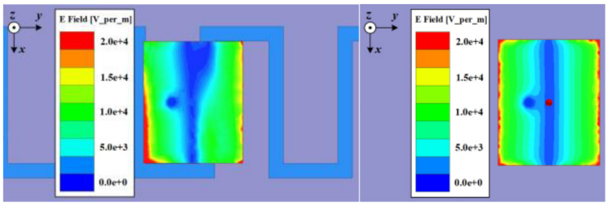


FIGURE 4. The gain of the proposed antenna at 5.8 GHz varying with the $n = -2$ Floquet mode, and the normalized phase constant in the leaky-wave operating band of the period structure at 5.8GHz.

leads to fluctuations of the gain in the normal direction at 5.8 GHz of the antenna. When $\beta_{z,2}/k_0$ is close to -0.7, the resonant point of the antenna is close to 5.8 GHz, and its gain in the normal direction reaches 10.0dBi. Note that the latter is the maximum gain of the antenna.



(a) (b)

FIGURE 5. The electric field distribution of the rectangular patch at 5.8 GHz. (a) The proposed high gain patch antenna. (b) The conventional rectangular microstrip patch antenna.

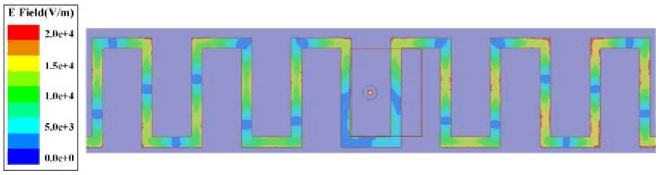


FIGURE 6. The electric field distribution of the periodic leaky-wave structure at 5.8 GHz.

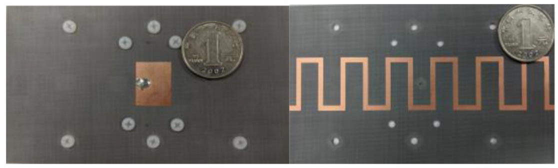
Therefore, the position of the frequency point can be adjusted by adjusting the size of the periodic leaky wave structure and changing its propagation constant. When the frequency point is adjusted back to the original resonance point of the rectangular patch, the equivalent permittivity of the dielectric plate highly changes, and the electric field on the patch is compressed. Simultaneously, the introduced structure increases the effective radiation aperture of the antenna and improves its gain.

The electric field distribution of the proposed antenna and the conventional patch antenna at the resonant frequencies of 5.8 GHz, are presented in Fig. 5. It can be seen that the electric field of the traditional antenna on the wide side of the patch is large and it has a uniform distribution, while that of the proposed antenna is quite different. More precisely, the electric field distribution of the proposed antenna (cf. Fig. 1) on the wide side is uneven. This is due to the fact that the dielectric constant of the dielectric plate is not uniform. The electric field distribution on the rectangular patch is affected, the effective radiation aperture is changed, and the gain is increased.

The electric field distribution of the periodic leaky-wave structure is also presented in Fig. 6. In this design, the rampart line works through the rectangular patch coupling. It can be seen that the electric field distribution is almost four zero points in one period. This means that the rampart line works for the $n = -2$ mode. However, it can be deduced from the simulation analysis that the radiation direction of the rampart line in this state is not broadside, and the radiation efficiency is very low as a leaky-wave structure. Thus, the rampart line contributes in increasing the radiation aperture by adjusting the equivalent permittivity.

III. GAIN-ENHANCED ANTENNA DESIGN

The proposed gain-enhanced patch antenna with a periodic microstrip rampart line (see Fig. 1) consists of a two-layer structure. Each layer has the same relative dielectric constant (ε_r) of 2.45, the same dielectric loss tangent (tan δ) of 0.0005 and the same thickness (h) of 0.8 mm. In addition, the total substrate thickness is 1.6 mm. The top layer is a rectangular patch which is consistent with the traditional rectangular patch antenna, the middle layer is a periodic microstrip rampart line and the bottom layer is a complete ground plane. The periodic leaky wave structure is perpendicular to the two radiating edges. It consists of six periods, while more periods will bring a greater loss and lower gain. The position of the feed connector is adjusted according to the matching. s is the width of the periodic microstrip rampart line, p is the length of each periodic unit cell of the periodic microstrip rampart line, and Wp is its width. L and W are respectively the length and width of the rectangular patch. Table 1 presents the values of the parameters of Fig. 1.



(a) (b)

FIGURE 7. (a) The rectangular patch in top layer of antenna. (b) The periodic microstrip rampart line in the middle layer of antenna.

TABLE 1. Parameters of the proposed antenna.

Symbol	Size (mm)	Symbol	Size (mm)
L	15.1	W	18.6
p	21	Wp	23.2
h	0.8	s	2.2

Fig. 7 presents the photograph of the gain-enhanced patch antenna with a periodic microstrip rampart line. The periodic leaky wave structure of six periodic units is sufficient to achieve the gain-enhanced characteristics. The dielectric plate consists of a double-layer stacked structure tightly bonded and fixed by nylon nuts.

IV. EXPERIMENTAL RESULTS

Fig. 8 shows the measured S-parameters (S_{11}) of the proposed gain-enhanced patch antenna with a periodic microstrip rampart line and the traditional patch antenna, which is close to the simulation. The resonance frequency (f) of the proposed antenna can be adjusted to 5.8 GHz, which is similar to that of the conventional rectangular patch antenna. The operating frequency bands of the two antennas are almost the same. It can be seen that the impedance bandwidth of the proposed antenna ($S_{11} < -10$ dB) is almost 4% (5.66 GHz-5.87 GHz), which is a little bit larger than that of the traditional antenna. Due to the periodic structure, the S-parameter (S_{11}) of the proposed antenna has a periodic variation along the wide frequency range.

Fig. 9 shows the simulated and measured radiation patterns of the xoz and yoz planes of the proposed gain-enhanced patch antenna and the traditional patch antenna, in the polar coordinate system. It can be seen that the radiation pattern of

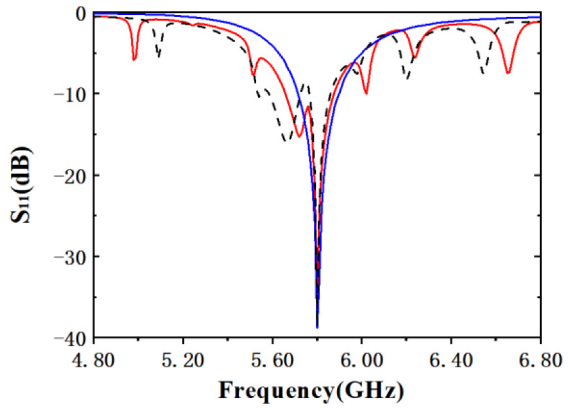


FIGURE 8. The measured *S*-parameter (S_{11}) of the proposed patch antenna and the conventional rectangular microstrip patch antenna.
— The measured S_{11} of the proposed high gain microstrip patch antenna with a periodic leaky wave structure (f = 5.8 GHz).
--- The simulated S_{11} of the proposed high gain microstrip patch antenna with a periodic leaky wave structure (f = 5.8 GHz).
— The measured S_{11} of the conventional rectangular microstrip patch antenna with a conventional substrate (f = 5.8 GHz).

the proposed antenna is similar to that of the traditional patch antenna. The gain of the proposed antenna (cf. Fig. 1) in the normal direction is 2.55 dB higher than that of the traditional patch antenna. As shown in Fig. 10, the measured gain of the proposed patch antenna is 10.0 dBi while that of the conventional patch antenna is 7.45 dBi. Consequently, the proposed antenna achieves a gain enhancement of almost 2.55 dB (or 79.9%). In addition, the proposed antenna reaches a good cross-polarized level with a front-to-back ratio of almost −15dB, which is comparable with that of the traditional patch antenna.

Fig. 10 shows a comparison of the measured gain curves of the proposed and traditional antennas in the normal direction, as well as the radiation efficiency curve of the proposed antenna. The gain of the proposed antenna is 2.55 dB higher than that of the traditional antenna. Both antennas reach the highest gain at the resonance point of 5.8 GHz. It can also be seen from Fig. 10 that, due to another resonance point around 5.75 GHz caused by the periodic structure, a dip exists in the S_{11} curves, and the antenna has a small gain at this resonance point.

Table 2 presents a comparison of the proposed antenna with existing high gain antennas, along with a simulated array of two conventional patches that are 0.9 λ_0 apart. Note that ΔGain denotes the value of improved gain referred to the traditional patch antenna working at the same frequency. Besides [16] which belongs to broadband antenna design, the bandwidth of the proposed antenna is close to that of the other high gain antennas. The gain of the proposed antenna is a little bit higher than that of [17] and [18]. However, it is lower than that of [15] and [16]. Compared with the array antenna, the proposed antenna achieves almost the same gains improvement with a larger volume. It is important to mention that this paper proposes a new concept to improve the gain of the traditional rectangular microstrip antenna. The method in [15] needs to be provided with metal vias, and

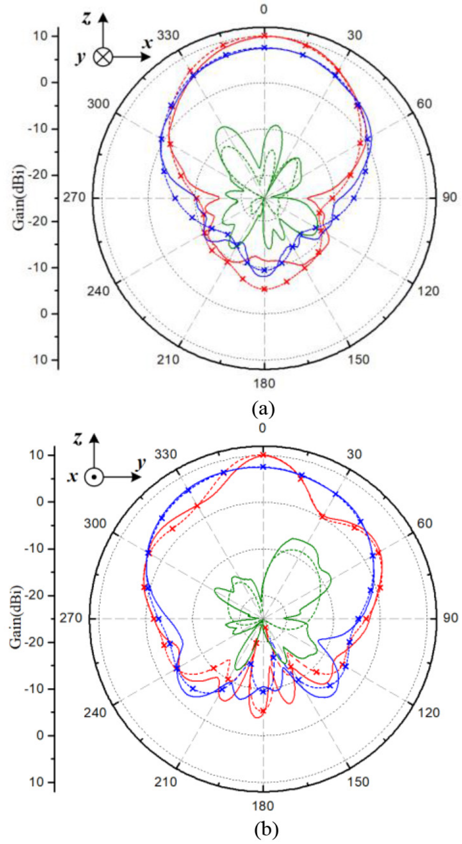


FIGURE 9. (a) Simulated and measured radiation patterns in the *xoz* plane in polar coordinates (f = 5.8 GHz). (b) Simulated radiation patterns in the *yoz* plane in polar coordinates (f = 5.8 GHz).
— The measured radiation patterns of the proposed antenna.
--- The simulated radiation patterns of the proposed antenna.
— The measured radiation patterns of the conventional antenna.
--- The simulated radiation patterns of the conventional antenna.
— The measured cross-polarization of the proposed antenna.
--- The simulated cross-polarization of the proposed antenna.

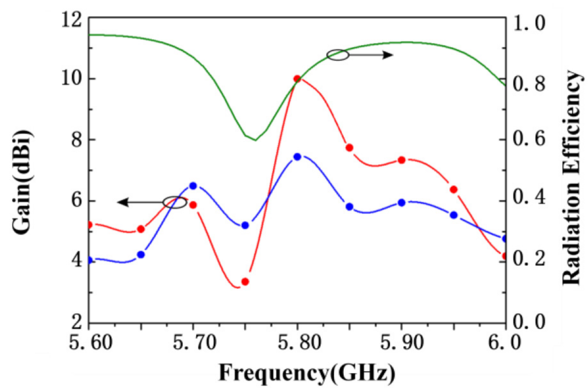


FIGURE 10. The measured gain curves in the normal direction, and the radiation efficiency curve.
— The proposed high gain microstrip patch antenna with a periodic leaky wave structure.
— The conventional rectangular microstrip patch antenna with a conventional substrate.
— The radiation efficiency curve of the proposed antenna.

therefore the array requires an additional feeding network. The methods in [16], [17] and [18] use a stacked design, which results in a complex structure for manufacturing. On

TABLE 2. Comparison of high gain antennas.

REF.	Freq. (GHz)	BW (%)	Gain (dBi)	Patch size (λ_0^2)	Volume (λ_0^3)	ΔGain (dB)
[15]	2.93	3.0	10.7	$0.61\lambda_0$*$0.61\lambda_0$	$1.66\lambda_0$*$1.66\lambda_0$*$0.03\lambda_0$	2.9
[16]	2.6	19	11	$0.56\lambda_0$*$0.54\lambda_0$	$1.19\lambda_0$*$1.19\lambda_0$*$0.08\lambda_0$	/
[17]	4.91	4.88	8.75	$0.51\lambda_0$*$0.51\lambda_0$	$1.03\lambda_0$*$1.03\lambda_0$*$0.05\lambda_0$	/
[18]	9.9	1.2	9.9	/	3.14*$1.74\lambda_0^2$*$0.04\lambda_0$	/
Array	5.8	1.7	10.2	/	$1.55\lambda_0$*$1.02\lambda_0$*$0.015\lambda_0$	2.65
Proposed antenna	5.8	4.0	10.0	$0.29\lambda_0$*$0.36\lambda_0$	$2.32\lambda_0$*$1.35\lambda_0$*$0.03\lambda_0$	2.55

the contrary, the proposed design does not need to punch metal vias, does not have a complex structure, and it uses the same manufacturing process as that of the traditional patch antennas.

V. CONCLUSION

This paper proposed a gain-enhanced patch antenna with a periodic microstrip rampart line. The proposed antenna consists of a rectangular patch, a substrate embedded with periodic leaky wave structure and a complete ground plane. The periodic microstrip rampart line changes the dielectric constant of the dielectric plate and affects the electric field distribution on the rectangular patch, so as to improve the gain. Some formulas are derived to calculate the equivalent permittivity of the proposed model, so as to calculate the high gain frequency point position. The simulated and measured results show an excellent agreement, thus demonstrating that using the proposed approach, a rectangular patch antenna can be raised to 10.0 dBi with excessive 2.55 dB (or 79.9%). The proposed design is an extension of a multi-frequency antenna, which results in a single-frequency high-gain antenna. It requires multiple periodic units, and therefore the ground area should be increased. Finally, the proposed method can efficiently improve the gain of the microstrip antenna. In future work, we aim at increasing the gain of multiple frequency points.

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