# A Compact Microstrip-Fed Patch Antenna With Enhanced Bandwidth and Harmonic Suppression

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***Abstract*—A single-layer microstrip-fed patch antenna with capabilities of both bandwidth enhancement and harmonic suppression is proposed. For this purpose, a pair of $\lambda$/4 microstrip-line resonators is introduced and coupled in proximity to a rectangular patch. The wideband property can be obtained by making effective use of the two resonances introduced by the radiating patch and nonradiating $\lambda$/4 resonators. Different from other reported dual-resonance patch antennas, the proposed antenna does not require the electrically thick substrate; so, it has attractive low-profile property. Thanks to the good features of $\lambda$/4 resonators and capacitive feeding scheme, harmonic radiating modes of the patch antenna can be significantly suppressed as highly demanded in modern highly-integrated communication systems. The working principle, equivalent circuit, and design procedure are extensively described. Finally, a prototype antenna operating at 4.9 GHz is designed and fabricated. The measured results show that its bandwidth is 2.7 times wider than that of the traditional insert-fed patch counterpart, and the harmful spurious radiation from other higher-order radiating modes has been effectively suppressed.**

***Index Terms*—Patch antenna, bandwidth enhancement, harmonic suppression, coupled feed, and quarter-wave resonator.**

## I. INTRODUCTION

IN modern communication and radar systems, the antenna and the front-end are placed closely or even integrated together [1]. In these systems, the microstrip patch antenna is much popular since it can be easily integrated with many other active and passive circuits such as filters, amplifiers, oscillators, and mixers. Despite these attractive features, the microstrip antenna usually suffers from several inherent drawbacks. One is the narrow bandwidth because of its resonant property with a high *Q*; the other is the high level of harmonic radiation, which will decrease the efficiency of the system and even cause harmful interferences with other systems.

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To enhance the bandwidth of patch antennas, many efforts have been made by using the aperture coupling feed [2], proximity coupling feed [3], or stacked patch configurations [4]-[6]. However, these techniques require multi-layer substrates, resulting in difficulty and high cost in fabrication. It is preferred to enhance the bandwidth of patch antennas using a single-layer coplanar-fed method. For this purpose, extensive studies have been reported in the literature, most of which employ the dual-resonance concept. It is well known that the patch antenna can be treated as a resonator with radiation loss. If another resonance is introduced to be incorporated with this resonating patch, the bandwidth is expected to increase significantly. A typical fed method is to adopt the modified probe with L-, T-, and hook-shaped configurations [7]-[10]. Another method is to load the radiating patch with different slots, e.g., U-, E-, and Ψ-shaped slots [11]-[15]. Recently, single-layer coplanar capacitive-fed patch antennas are reported in [16]-[19], which are relatively simple to fabricate and assemble. But, these wideband antennas are only valid when their electrical heights or thicknesses are no less than $0.1\lambda_0$. As such, an additional foam- or air-layer needs to be introduced, especially at low frequency. Consequently, these antennas suffer from difficulty in assembling. In addition, most of them can only be fed by the probes.

When compared with the probe-fed method, the microstrip-fed approach is much useful in the implementation of an array antenna with a number of radiating elements. In this context, the microstrip feeding network and patch radiating elements can be fully integrated on a single-layer substrate and the entire array can be fabricated simultaneously by using the printing technology. However, the thickness of the dielectric substrate must be electrically small, so that it brings a challenging task in the design of a wideband microstrip-fed patch antenna on a single-layer substrate. So far, a few techniques have been reported to solve this problem. In [20], additional nonradiating resonators are employed to construct an impedance-matching network. In [21] and [22], a half-wavelength ($\lambda$/2) resonator and a composite right-/left-handed resonator are employed, respectively, to achieve the wideband performance. Since the sizes of the feeding networks are significantly enlarged, these approaches can hardly be applied in the design of an array. A size-miniaturization method is reported in [23], but the patch configuration is destroyed by an extra T-shaped resonator. Moreover, the harmonic radiation cannot be suppressed because this T-shaped resonator operates as a $\lambda$/2 resonator.

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With regard to the harmonic radiation, many solutions have been reported to solve this problem. The simplest method is to connect a filter to the patch [24], but it will increase the overall size of the antenna system. Recently, research efforts are focused on applying kinds of periodic structures to solve the problem, including electromagnetic bandgap structure (EBG), defected ground structures (DGS), and compact microstrip resonant cell (CMRC) [25-28]. However, the etched structures on the ground plane will degrade the front-to-back radiation ratio.

In this paper, a microstrip-fed patch antenna with enhanced bandwidth and good harmonic suppression performance is presented. As reported in [29], a patch could be capacitively fed by a coupling gap. In our method, a pair of $\lambda/4$ resonators is employed and placed in proximity to the radiating patch for wideband radiation under dual resonances. The advantages of this method are as follows: (1) Operating bandwidth of a single-layer patch antenna is enhanced even for an electrically thin substrate, and it can be further controlled to some extent by adjusting the gap width between the patch and the $\lambda/4$ resonators; (2) Harmonic radiation at high frequency is effectively suppressed thanks to the characteristics of capacitive feeding structure and $\lambda/4$ resonators; (3) The feeding-line section is small in size so as not to increase the overall size of the patch antenna in array applications; (4) The whole antenna structure is geometrically symmetric so as to maintain a low cross-polarization level. The remainder of this paper is organized as follows. The geometry and working principle of the proposed antenna are presented in Section II. The equivalent circuit and design procedure are provided in Section III. To validate the design method, a prototype antenna is designed, fabricated and tested as presented in Section IV. Conclusions are drawn in Section V.

## II. Geometry and Working Principle

### A. Geometry

The proposed single-layer microstrip-fed patch antenna with bandwidth enhancement and harmonic suppression is depicted in Fig. 1. The antenna is composed of a rectangular patch and two $\lambda/4$ resonators in the feeding line section. The two $\lambda/4$ resonators share a shorting pin with a radius of $r$. The dimensions of the patch are $L_p \times W_p$, and those of each $\lambda/4$ resonator are $L_r \times W_r$. Different from the traditional insert-fed method, the radiating patch and feeding line are interacted through the $\lambda/4$ resonators which are located at a distance $d$ from the patch. All of them can be fabricated on a single-layer substrate with a thickness of $h$ and a relative permittivity of $\varepsilon_r$.

### B. Working Principle

A resonator-type patch antenna usually requires an electrically thin substrate, thus suffering from a narrow bandwidth. An effective method for bandwidth enhancement is to construct a dual-resonance structure. For this purpose, an extra nonradiating resonator is usually introduced in proximity to the radiating patch. For example, by making use of the L-probe [7] or coplanar capacitive-coupled probe-fed structure [16], the reactance introduced by the probe and the capacitance introduced by the other capacitive part can make up an extra lumped resonating circuit. The dual resonances introduced by the patch and the extra resonating circuit could be adjusted close to each other; thus, a wideband performance could be achieved. But, the methods in [7] and [16] are only valid for a thick substrate. For a thin substrate used mostly in microstrip patch antennas, the reactance of the probe is too small to excite the extra resonance.

Instead of the above lumped resonator in a thick substrate, a pair of $\lambda/4$ resonators is employed herein to form a coplanar distributed resonator, which is placed in proximity to the main patch as depicted in Fig. 1. The coupling gap plays a key role in achieving a wideband performance. Its width affects the dual resonant frequencies significantly. Therefore, the gap width can be optimized to make the two resonant frequencies close to each other, thus combining two narrower bands into a single wide band. Because the second resonance only relates to the $\lambda/4$ resonator and the coupling gap, this proposed method is valid for varied substrate thicknesses.

In addition to bandwidth enhancement, the proposed feeding method can effectively suppress the spurious radiation caused by harmonic resonant modes of the patch radiator. It can be intuitively explained in the following two aspects. On the one hand, the patch antenna is capacitively fed through a pair of $\lambda/4$ resonators. In this case, the energy can only be transmitted to the patch in discrete frequencies where both the patch and $\lambda/4$ resonators are resonating, which is completely different from the traditional insert-fed patch antenna [30]. On the other hand, all the even-order resonant modes could not be excited in the $\lambda/4$ resonators because of the shorting pin introduced in the central plane. As discussed in [31]-[32], the 2$^{nd}$-order mode is the most harmful mode, but it can be naturally suppressed because of its even symmetrical property in the transverse plane.

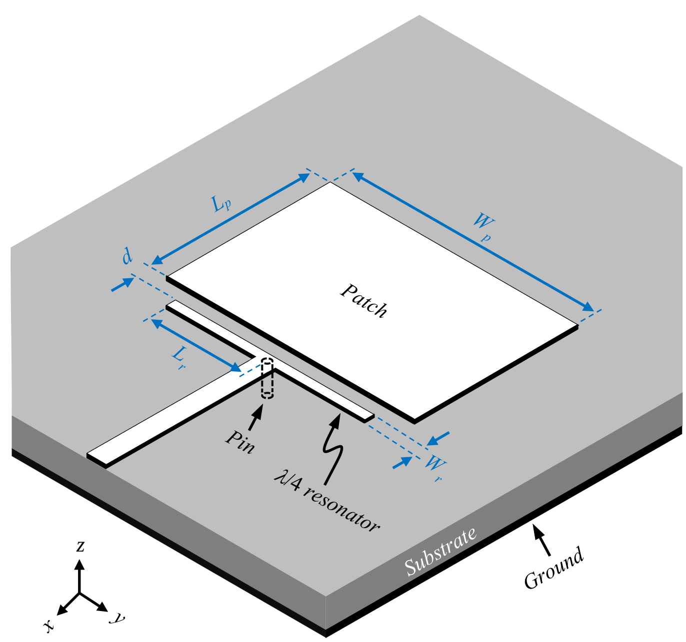


Fig. 1. Geometry of the proposed wideband patch antenna.

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## III. Analysis, Design, and Investigation

### A. Equivalent Circuit

Fig. 2 depicts the equivalent circuit model of the proposed antenna. Herein, the rectangular patch, i.e., the 1st resonator, is represented by a lossy resonator of $R_1L_1C_1$, whose values can be calculated by the transmission-line or cavity model in [29]. Each $\lambda/4$ resonator, i.e., the 2nd resonator, is represented by a lossless resonator of $L_2C_2$, whose values can be calculated from [32]. Since the two $\lambda/4$ resonators share a common shorting pin, they are represented by two identical branches in parallel.

A small gap is introduced between the paired $\lambda/4$ resonators and the radiating patch to provide a capacitive coupling. Its equivalent circuit can be modeled by a $\pi$-type network with three capacitances, $C_g$, $C_{s1}$, and $C_{s2}$. These capacitances can be numerically de-embedded. The effect of the gap in the proposed antenna will be discussed in the following section.

The shorting pin is an important component. In our analysis, the reactance introduced by this pin is taken into consideration and it is reasonably modeled as a reactance $L_{pin}$, which can be approximated as [33]

$$L_{pin} \approx \frac{\eta}{2\pi} kh \left[ \ln\left(\frac{2}{kr}\right) - \gamma \right] \tag{1}$$

where $\eta$ and $k$ are the wave impedance and wavenumber, $h$ and $r$ are the height and radius of the shorting pin, and $\gamma$ is the Euler's constant with $\gamma = 0.5772$.

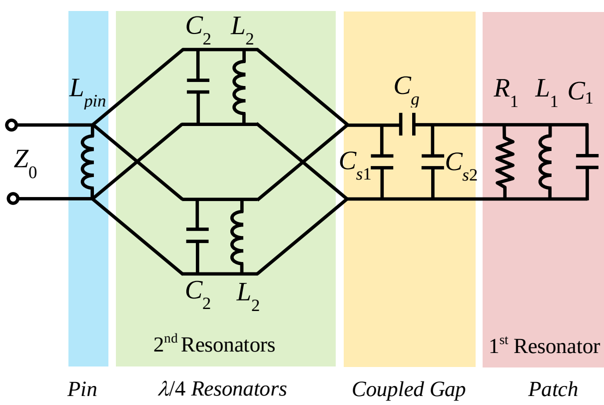


Fig. 2. Equivalent circuit model of the proposed patch antenna in Fig. 1.

### B. Design Method

Because of the compact and symmetrical geometry of the proposed antenna, there are only a few parameters to be determined in our antenna design. The design procedure involves the following two steps. The first step is to determine the sizes of the patch ($L_p \times W_p$) and $\lambda/4$ resonators ($L_r \times W_r$) according to the specified central frequency $f_0$. Resonant frequencies of the patch and $\lambda/4$ resonator are mainly dependent on their lengths, $L_p$ and $L_r$, respectively, which can be estimated as [29], [32]:

$$L_p = \frac{1}{2 f_0 \sqrt{\varepsilon_{rp}} \sqrt{\mu_0 \varepsilon_0}} - 2\Delta L \tag{2}$$

$$L_r = \frac{1}{f_0 \sqrt{\varepsilon_{rr}} \sqrt{\mu_0 \varepsilon_0}} \tag{3}$$

where $\Delta L$ is the effective extended length because of the parasitic effects at the two edges of a rectangular patch [34]. $\mu_0$ and $\varepsilon_0$ are the permeability and permittivity in free space, respectively. $\varepsilon_{rp}$ and $\varepsilon_{rr}$ are the effective permittivities for the patch and $\lambda/4$ resonators, which can be calculated by using

$$\varepsilon_{ri} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12h/W_i}} \qquad i = p, r \tag{4}$$

The second step is to determine the width $d$ of the gap. Because of the emergence of two resonances introduced by the patch and the paired $\lambda/4$ resonators, two reflection poles can be expected to appear in the reflection coefficient. These two poles can be appropriately adjusted by the gap width $d$, aiming to realize a dual-pole wideband performance.

To show the effectiveness of the design method, a patch operating at a central frequency of 4.9 GHz is designed as an example. The antenna is implemented on the Rogers Duroid 5870 substrate with a relative permittivity of $\varepsilon_r$ = 2.33 and thickness of $h$ = 1.57 mm (0.026 $\lambda_0$). Then, we use a full-wave simulation software HFSS to simulate the performance of this patch antenna. The sizes of the patch and $\lambda/4$ resonator are chosen as 18 mm × 27 mm and 11.08 mm × 0.5 mm, respectively, and the radius of the shorting pin is set as $r$ = 0.5 mm.

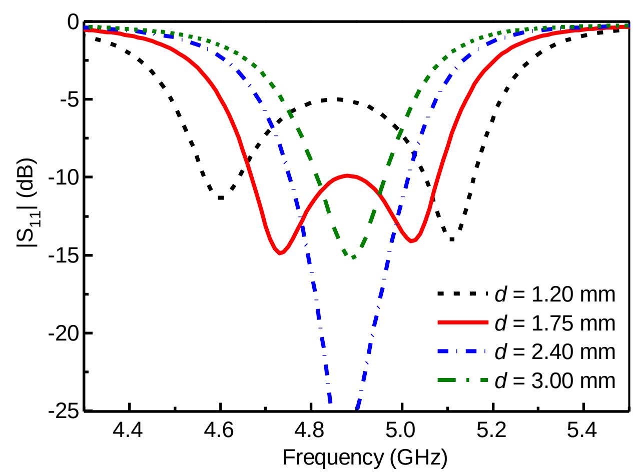


Fig. 3. Influence of coupling gap $d$ on the reflection coefficient.

Fig. 3 displays the variation of reflection coefficients with respect to $d$. As the two resonators are closely placed with $d$ = 1.2 mm, two reflection poles can be observed in Fig. 3. However, they are far away from each other, which can be applied to design a dual-frequency antenna. With the increase in $d$, the two poles gradually close up and are finally combined together to create a wide operating band when $d$ = 1.75 mm. In this case, the bandwidth reaches its maximum, which is nearly three times wider than that of a traditional patch antenna formed on the same substrate. If $d$ is further increased, the two poles are merged into a single pole at $d$ = 2.4 mm, and then poor impedance matching happens at $d$ = 3 mm or more. Against the

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traditional insert-fed patch antenna, the proposed patch antenna can achieve adjustable bandwidth as illustrated in Fig. 3.

Generally speaking, acceptable performance can be obtained after the above two steps are executed. The shorting pin in the feeding structure is a portion of the paired $\lambda/4$ resonators and its radius $r$ can be chosen arbitrarily. However, we can understand from (1) that the value of the inductance introduced by this pin is strongly dependent on the radius of this pin. Fig. 4 displays the variation of the simulated reflection coefficients with respect to pin radius $r$. We can figure out that the pin radius has little influence on the reflection coefficient herein.

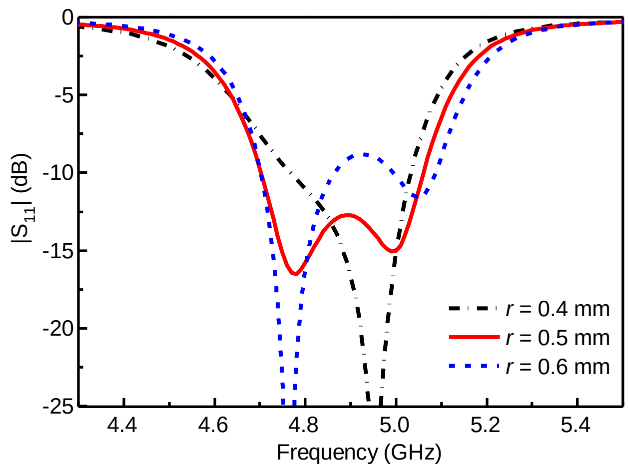



Fig. 4. Influence of shorting pin radius $r$ on the reflection coefficient.

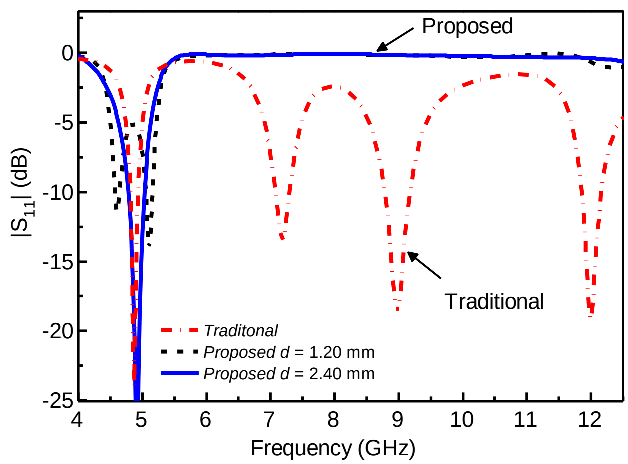


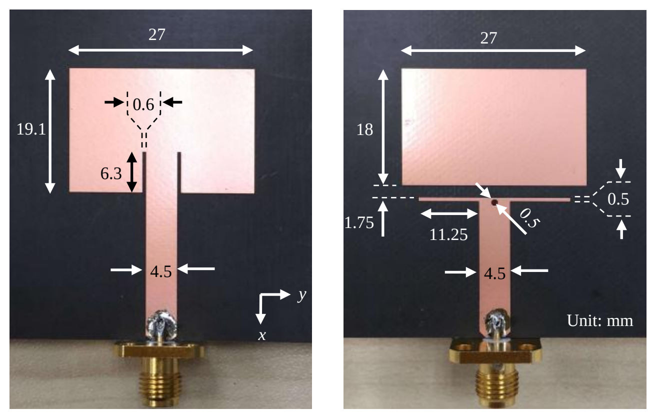

Fig. 5. Simulated reflection coefficients of the proposed and traditional patch antennas in a wide frequency range.

## C. *Harmonic Suppression*

In addition to bandwidth enhancement as described above, the undesired harmonic radiation at high frequencies can be effectively suppressed by the proposed technique. Fig. 5 displays the simulated reflection coefficients in a wide frequency range under two different $d$ values. For comparison, the result of a traditional insert-fed patch operating at 4.9 GHz is also plotted in the same figure. There are many higher-order radiating modes beyond the dominant $TM_{10}$ mode for the insert-fed patch. However, most of them will disappear in the proposed patch antennas, thereby validating the effective suppression of harmonic radiations. Comparing the results of $d$ = 1.2 mm and $d$ = 2.4 mm, we can further figure out that the effectiveness of the harmonic suppression is hardly influenced by the gap width and operation bandwidth.

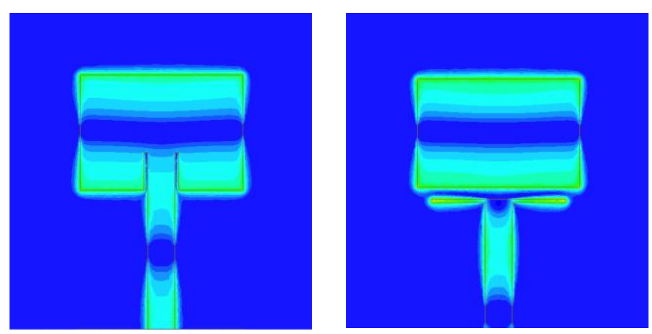
# IV. Experimental Verification

To examine the effectiveness of this technique, a patch antenna prototype using the proposed technique is designed in this section, and its performance will be investigated against the traditional insert-fed antenna. Both of them operate at 4.9 GHz and are fabricated on the Rogers Duroid 5870 substrates with a relative permittivity of $\varepsilon_r$ = 2.33 and a thickness of $h$ = 1.57 mm. Fig. 6 gives a photograph of these two fabricated patch prototypes with a few main parameters denoted. The simulated electric-field distributions of the two patches at a central frequency 4.9 GHz are depicted in Fig. 7. We can see that the radiation is produced at both the upper and lower edges, meaning that these two patch antennas are both operating at $TM_{10}$ mode. However, the field distribution on the proposed patch is more symmetrical since it is not disturbed by the feed line because of capacitive or noncontacting feeding scheme.




(a) (b)

Fig. 6. Photographs of fabricated prototypes. (a) Traditional. (b) Proposed.



(a) (b)

Fig. 7. Electric field distributions of two patches. (a) Traditional. (b) Proposed.

## A. *Bandwidth Enhancement*

In measurement, the reflection coefficients, $|S_{11}|$, of the two fabricated patch antennas are measured by an Agilent N5230A vector network analyzer (VNA). The simulated and measured results in the operating band around 4.9 GHz are given in Fig. 8. The simulated and measured results are found in good agreement with each other, thus confirming the predicted performances of these two antennas. The measured frequency range of the proposed patch antenna with $|S_{11}|$ lower than -10dB is 4.69-5.10 GHz (8.4%), while that of the traditional patch is

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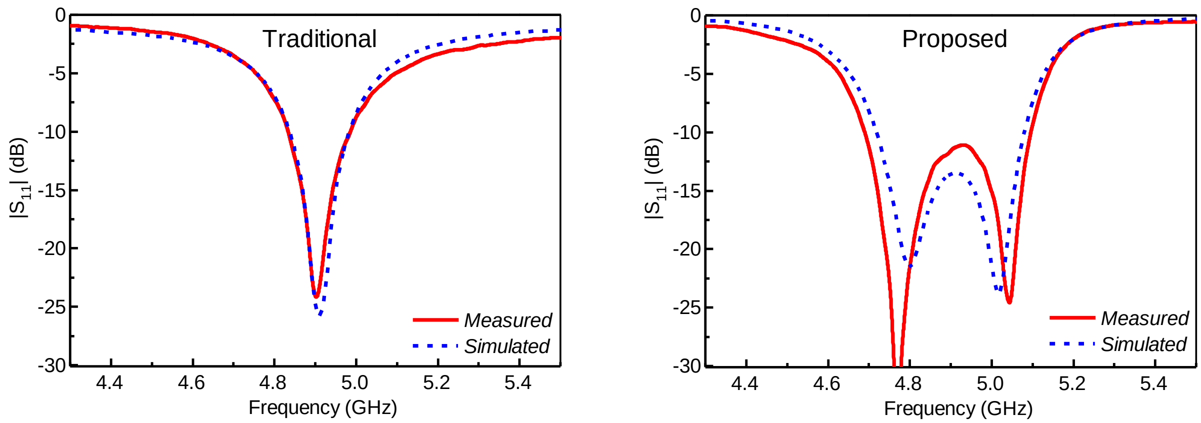
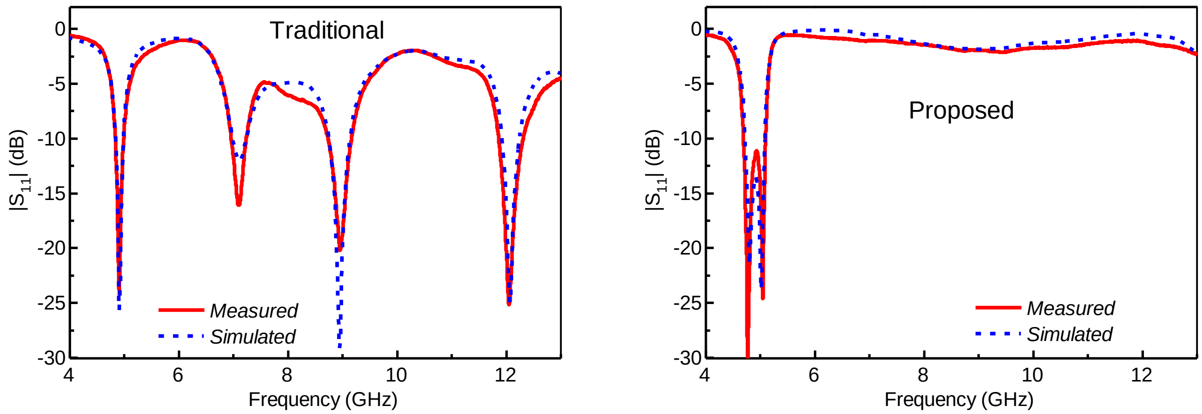


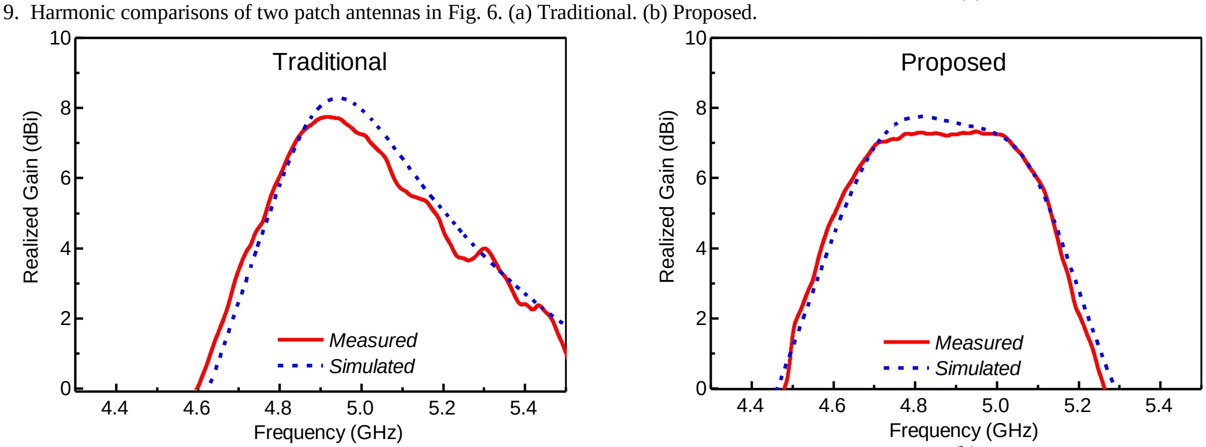
(a) (b)

Fig. 8. Bandwidth comparisons of two patch antennas in Fig. 6. (a) Traditional. (b) Proposed.



(a) (b)

Fig. 9. Harmonic comparisons of two patch antennas in Fig. 6. (a) Traditional. (b) Proposed.



(a) (b)

Fig. 10. Gain-response comparisons of two patch antennas in Fig. 6. (a) Traditional. (b) Proposed.

4.82-4.97 GHz (3.1%). It means that the bandwidth of our proposed antenna has been enhanced by 2.7 times.

### *B. Harmonic Suppression*

Harmonic suppression for radiation is another advantage of the proposed patch antenna. To show this advantage evidently, the $|S_{11}|$ of these two patches are plotted together in Fig. 9 in a wide frequency range. Different from the traditional one with multiple-mode radiations as plotted in Fig. 9(a), our proposed patch antenna has successfully suppressed most of higher modes as depicted in Fig. 9(b). The simulated and measured results agree well with each other in the entire plotted range.

### *C. Gains*

The gains of these two patch antennas were measured by using the SATIMO near-field antenna measurement system, and the relevant results are shown in Fig. 10. For the traditional patch antenna in Fig. 10(a), there is a peak of 7.8 dBi in the gain response. For the proposed one in Fig. 10(b), there is a flat range around the central frequency and its maximum value is about 7.3 dBi. In addition, the gain response of our proposed

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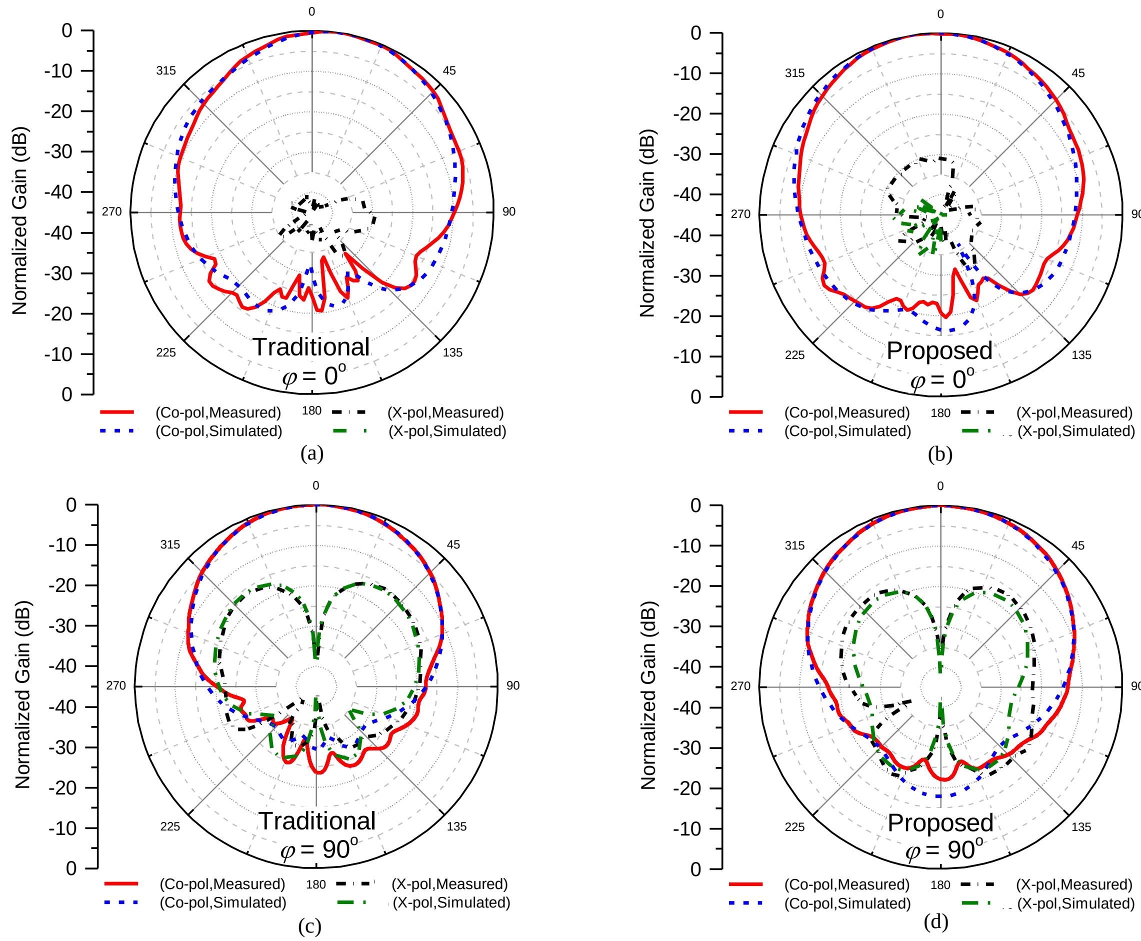


Fig. 11. Comparisons in radiation patterns of two patch antennas in Fig. 6. (a) and (c) Traditional $\varphi = 0°$ and $\varphi = 90°$. (b) and (d) Proposed $\varphi = 0°$ and $\varphi = 90°$.

antenna is more symmetric with respect to the central frequency. The 3-dB gain bandwidths of the traditional and proposed patches are 430 and 570 MHz, respectively.

### *D. Radiation Patterns*

The radiation patterns of the two patches are measured too. The simulated and measured results in the $\varphi = 0°$ and $\varphi = 90°$ planes are plotted in Fig. 11. Generally speaking, the main parameters of radiation patterns, such as beamwidth and cross polarization levels of these two antennas, are very similar to each other. The 3-dB beamwidths of the traditional and proposed patch antennas are found to be 68° and 75°, respectively. The measured cross-polarization levels in the boresight direction are both lower than -31 dB. It should be noted that the maximum radiation direction, as shown in Fig. 11(a) for the traditional patch, appears at $\theta = 10°$, as it is influenced by the microstrip feed line as indicated in Fig. 7. The radiation pattern in Fig. 11(b) for the proposed patch antenna is more symmetric.

## V. Conclusion

This paper presents a new compact coupled-fed patch antenna in a single-layer substrate. By using a pair of $\lambda/4$ resonators, the bandwidth of the patch antenna is significantly enlarged and the harmonic radiations are effectively suppressed, while other advantages of the patch antenna, such as low cost, low profile, and easy integration, still remain. In the analysis, an equivalent circuit model is proposed to analyze and design this proposed antenna. Our investigation shows that the bandwidth of this patch can be widened by adjusting the gap between the patch and the $\lambda/4$ resonator. To validate the design method, a prototype antenna operating at 4.9 GHz is designed and fabricated. Its good performance is demonstrated by comparison with a traditional insert-fed patch antenna. The measured and simulated results show that the bandwidth has been enlarged by 2.7 times and the higher-mode radiations have been successfully suppressed. In addition, more symmetric radiation patterns and gains have been obtained.

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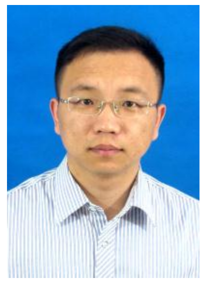

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