Ijaiem.com/Mar 2025/ Volume 14/Issue 1/Article No-1/81-85
ISSN: 2319-4847

AN ASYMMETRICAL PSI-SHAPED MULTIBAND ANTENNA FOR WIRELESS APPLICATIONS

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Article Info

Received: 06-01-2025 ***Revised: 12 -02-2025*** ***Accepted: 22-02-2025*** ***Published:07/03/2025***

***Abstract*—A novel multiband patch antenna with uni- directional radiation is proposed by integrating resonators in the design. The multiple frequency bands are achieved based on a coupled resonators network. The topology and design methodology are detailed. The patch not only works as the last-order resonator of the network but also the radiating element. Using this approach, multiple bands can be achieved without changing the shape of the radiation element. In addition, the operation bands can be adjusted by adjusting the coupling between the resonators. In this work, the four bands are designed at 4.6, 5.05, 5.8 and 6.3 GHz as a proof-of-concept. The prototype is fabricated and tested and measured results agree very well with the simulations, showing an excellent performance in terms of impedance matching, radiation patterns, gains and cross polarization discrimination (XPD).**

***Index Terms*— Multiband, patch antenna, resonator-based, unidirectional.**

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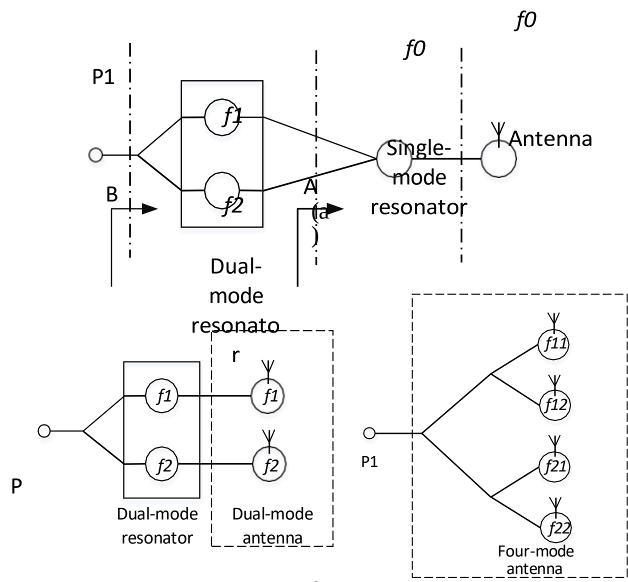
I. Introduction

The recent advancements in wireless communication technologies are facilitating a range of applications, including GSM, CDMA, LTE, Wi-Fi, and WLAN. Antennas, serving as the essential components for transmitting and receiving signals in communication systems, must possess characteristics such as compact size, high integration, and lightweight design to minimize the costs associated with large-scale industrial production. To address the need for multiband functionality, designing a broadband antenna that encompasses all relevant applications and frequency bands is a practical approach. Additionally, multiband antennas are considered another viable solution to achieve this objective. In certain applications where high gain and specific polarization are critical, antennas that offer multiband capabilities along with uni-directional radiation patterns are also necessary.

Numerous approaches for the design of antennas capable of multiband operation have been explored [1]-[10]. In applications that require compactness and portability, where the purity of polarization is not a critical factor, the planar inverted-F antenna (PIFA) is frequently utilized to facilitate multiband functionality [1]. Reference [2] demonstrates the achievement of dual and tri-band operations through the incorporation of both fundamental and spurious frequencies of the radiating element. Studies [3]-[5] present multiband antennas exhibiting unidirectional radiation by integrating slots or parasitic stubs onto the radiator. Additionally, for unidirectional antennas, multiple frequency bands can be attained by stacking patches of varying sizes; however, this approach results in increased thickness and complexity [6].



(b) (c)

Fig. 1. The resonator-based topology: (a) topology of the proposed four-band antenna, (b) equivalent topology see from interface A, (c) equivalent topology see from interface B.

Another proposed solution to achieve multiband operation with unidirectional radiation is inserting U-shaped slots in the radiator [7]-[9]. However, such kind of antennas have a poor polarization purity over the different bands, and thus it is not appropriate for using as a transmitter. Besides, those antennas cannot be extended for dual polarizations application due to the asymmetry of the radiating elements.

In this paper, A novel unidirectional patch antenna featuring four distinct operational frequency bands is proposed for wireless communication applications, based on a coupled resonator circuit model. Unlike conventional multiband antennas, this design achieves its four frequency bands through the integration of specific resonators. The operational frequency bands can be fine-tuned by adjusting the coupling between these resonators. The prototype has been optimized and tested, with the measured results demonstrating a strong correlation with the simulation outcomes.

II. Topology and Equivalent Circuits

Figure 1(a) illustrates the proposed configuration for a four-band antenna. This configuration consists of two first-order resonators and one second-order resonator, enabling the attainment of fourth-order resonant characteristics. The circles denote the resonators, while the lines indicate the coupling between them. It is important to highlight that the patch functions not only as the radiating element but also as the final resonator in the network.

The design concept is detailed as follows. First, the dimension of the patch is chosen with its resonant frequency ($f0$) located around the central frequency of the four designate operation bands. Then, the patch is coupled to a single-mode resonator which has the same resonant frequency ($f0$). By adjusting the coupling between them, the resonator-fed patch can split into two resonant frequencies, denoted as $f1$ and $f2$. Seeing from the interface A in Fig. 1(a), the coupled resonator-patch is equivalent to a dual-band antenna ($f1$, $f2$) and thus the topology is converted to the topology in Fig. 1(b). The coupled resonator-patch is then coupled to a dual-mode resonator which also has the resonant frequencies of $f1$ and $f2$. The dual-mode resonator and the dual-band antenna are tuned at each band respectively, generating two groups of resonant frequencies: $f11$, $f12$ and $f21$, $f22$. These four resonant frequencies will result in four distinct frequency bands. Seeing from the port (interface B), the topology in Fig. 1(a) can be equivalent to a four-band antenna, as shown in Fig. 1(c). The topology study provide a new circuit method to achieve multiband antenna using a single-mode antenna.

III. Antenna Design

A. Configuration

A multiband patch antenna has been designed based on the topology illustrated in Fig. 1(a), with its configuration depicted in Fig. 2. This antenna consists of two stacked substrates separated by a 1mm foam layer. The radiating element, or patch, is printed on the upper substrate's top layer, while the resonators and feeding network are located on the bottom layer of the lower substrate. Both layers utilize a common ground plane situated in the center. A slot is etched into the ground plane to facilitate the coupling of electromagnetic energy from the resonator on the lower layer to the patch on the upper layer. Additionally, the hairpin is coupled to a dual-mode stub-loaded resonator (SLR). The design employs Rogers 4003 substrate, characterized by a relative permittivity of 3.55 and a loss tangent of 0.0027.

Since the TM10 mode of the patch is used in the design, the dimension of the patch is about half-wavelength. The dimensions of the hairpin and the SLR can be approximately calculated using the following expressions [10-12],

$$2L1+L2 \approx \frac{c}{2 f_0 \sqrt{\varepsilon_{eff\ 2}}} \approx Lp \quad (1)$$

$$2L1+L3 \approx \frac{c}{2 f1 \sqrt{\varepsilon_{eff\ 2}}} \quad (2)$$

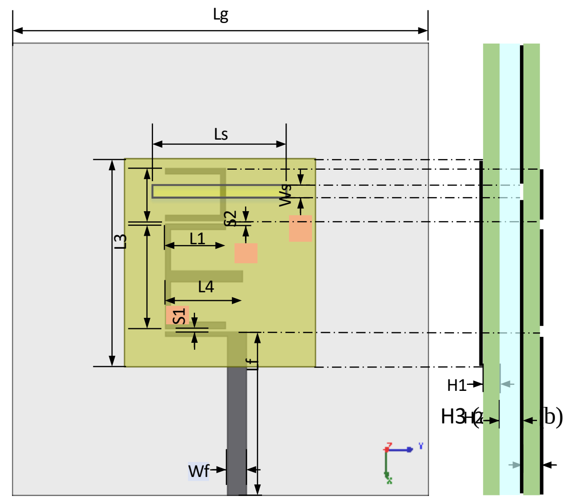


Fig. 2. Configuration of the proposed four-band patch antenna: (a) top view, (b) side view.

TABLE I
PARAMETERS OF THE ANTENNA PROPOSED: (MM)

Lg	Lp	Ls	Lf	L1	L2	L3	L4
50	17.6	12.4	18.7	5.5	4.5	8.8	7
Wf	Ws	S1	S2	H1	H2	H3	
1.8	0.9	0.25	0.25	0.813	1	0.813	

where, ε_{eff} is the effective relative permitivity, c is the speed of light in free space. $f1$ and $f2$ are the odd- and even-mode resonant frequencies of the SLR. The design and optimization were performed using HFSS 15, and the optimized parameters are presented in Table I.

B. Design methodology

To develop a four-band patch antenna, the initial step involves the design of a dual-band antenna. Based on filter design principles, second-order resonant characteristics can be realized when the patch is simultaneously tuned with a single-mode resonator, facilitating dual-band functionality. The positioning of the two frequency bands can be modified by adjusting the coupling intensity between them. Figure 3 illustrates the simulated S11 and the configuration of the dual-band patch antenna. The hairpin and the patch are specifically designed to resonate at 5.4 GHz. It is evident that two frequency bands at 4.8 GHz and 5.85 GHz are successfully achieved.

In this design, Coupling is crucial for modifying the positions of the two resonant modes. In this context, a combination of electric and magnetic coupling is employed between the resonators. The strength of the coupling can be regulated by altering the dimensions of the coupling slot in the ground. Figure 4 illustrates the results of the extracted ratio of f2 to f1 for various lengths of the coupling slot, as denoted by Ls in Figure 2. It is evident that the ratio of f2 to f1 rises from 1.05 to 1.32 as the length of the slot increases from 7 mm to 16 mm.

In order to obtain four frequency bands, the dual-band hairpin-patch is coupled to a SLR. The two operation bands and the two modes of the resonator are synchronically tuned. As a result, the two frequency bands ($f1$ and $f2$) are split into four resonant modes, denoted as $f11$, $f12$ and $f21$, $f22$ and four

Ijaiem.com/Mar 2025/ Volume 14/Issue 1/Article No-1/81-85
ISSN: 2319-4847

$$L1 + \frac{L3}{2} + L4 \approx \frac{c}{2 f_2 \sqrt{\varepsilon_{eff\,2}}} \quad (3)$$

operation bands are obtained. The locations of the four bands can be controlled by adjusting the coupling strength between the SLR and the hairpin. Fig. 5 shows the extracted ratios of

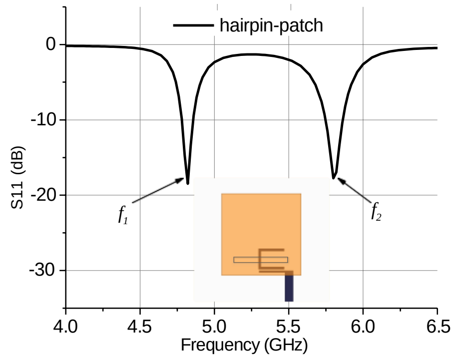


Fig. 3. The simulated S_{11} and the configuration of the dual-band antenna.

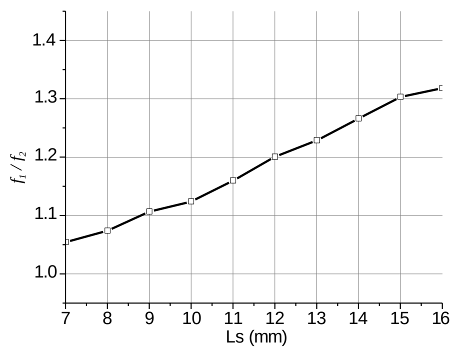
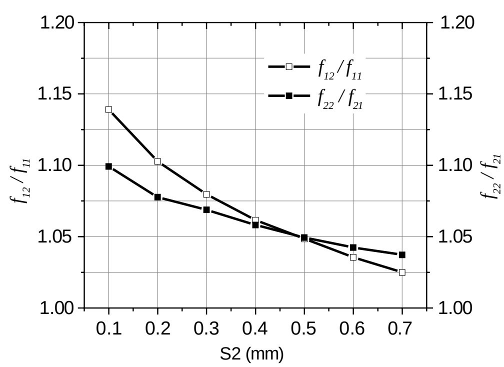


Fig. 4. The ratio of the two bands with different lengths of the slot.



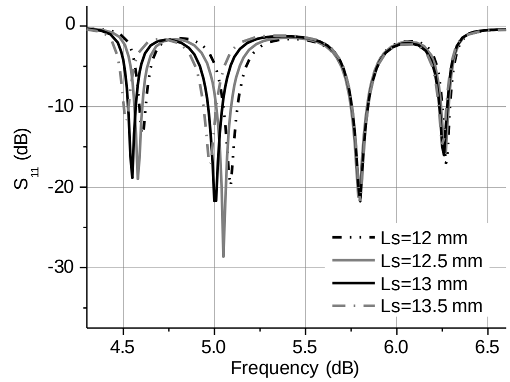


Fig. 6. The S_{11} of the four-band antenna with different *Ls*.

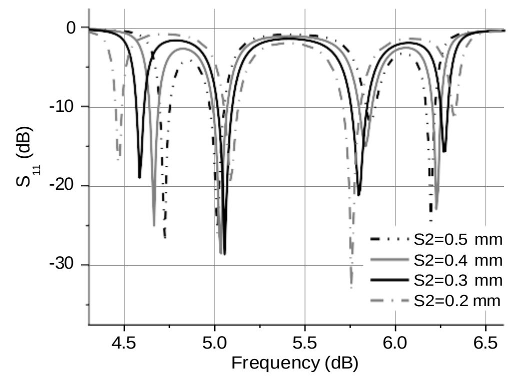


Fig. 7. The S_{11} of the four-band antenna with different *S2*.

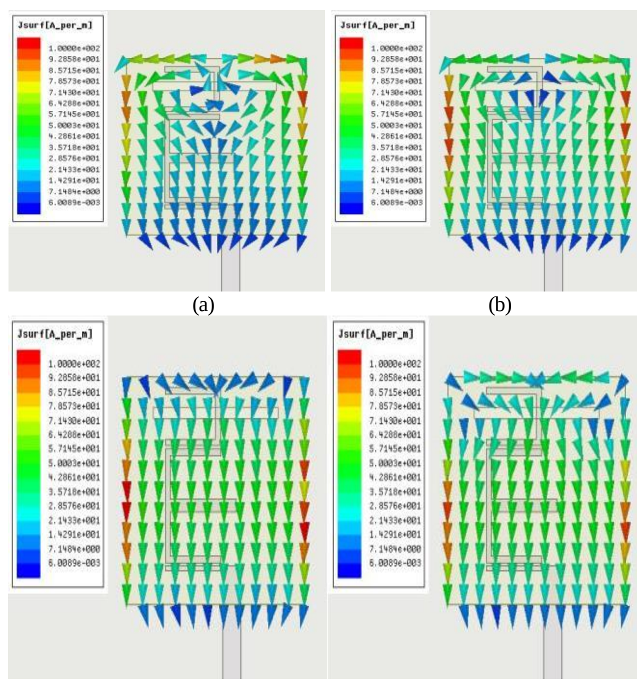


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Fig. 5. The frequency ratios of f_{12} / f_{11} and f_{22} / f_{21} with different *S2*.

the first two frequency bands (f_{12} / f_{11}) and the last two frequency bands (f_{22} / f_{21}) with different *S2*. When *S2* increases from 0.1 to 0.7 mm, the ratios of f_{12} and f_{11} (f_{22} and f_{21}) are decreases correspondingly.

Fig. 6 shows the simulated S_{11} of the proposed four-band patch antenna with different lengths of the slot, *Ls*. It is observed the first and the second bands move to lower frequency band simultaneously as the *Ls* increases from 12 to 13.5 mm while the third and the fourth bands maintain unchanged. Fig. 7 shows the S_{11} of the antenna with different spaces between the SLR and hairpin, *S2*. As can be seen, when the *S2* reduces from 0.5 mm to 0.2 mm, the first and the third bands moves to lower band whereas the second and the fourth bands moves to higher band.

C. Current Distribution

As a proof-of-concept, the four bands of the antenna are designed at 4.6, 5.05, 5.8 and 6.3 GHz. Fig. 8 shows the current distribution of the antenna at the four frequencies. It is

(c) (d)

Fig. 8. The current distribution at the four operating frequencies: (a) 4.6 GHz, (b) 5.05 GHz, (c) 5.8 GHz and (d) 6.3 GHz.

observed that the antenna has a similar current distribution characteristics at the four bands and therefore the antenna has consistent radiation patterns and high polarization purity at the four bands.

IV. Results and Discussion

Fig. 9 shows the simulated and measured S_{11} of the proposed four-band patch antenna. As can be observed, the

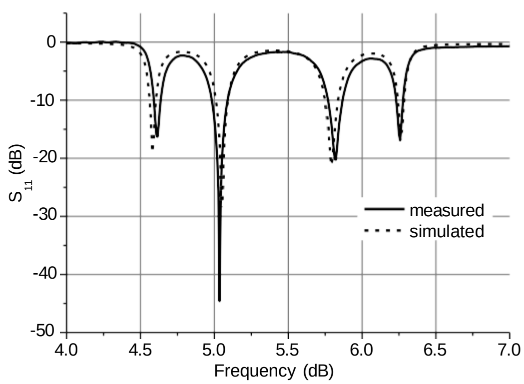


Fig. 9. The simulated and measured S_{11} of the proposed antenna.

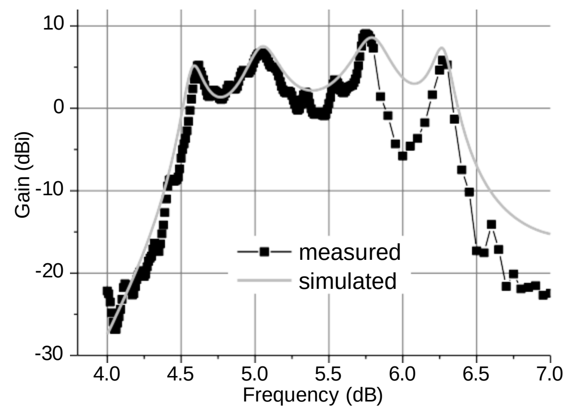
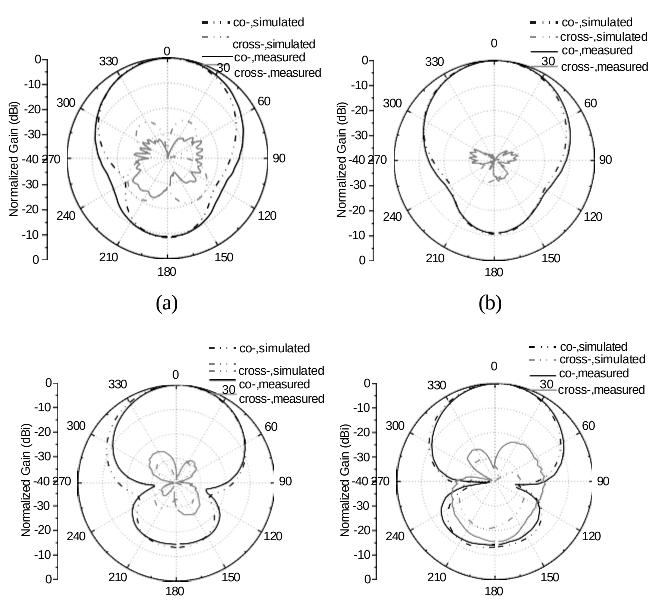


Fig. 11. The simulated and measured antenna gains.



(a) (b) (c) (d)

Fig. 10. The simulated and measured normalized E-plane radiation patterns at the four frequencies: (a) 4.6 GHz, (b) 5.05 GHz, (d) 5.8 GHz and (d) 6.3 GHz.

measured result agrees very well with the simulation, showing four operation bands at around 4.6, 5.05, 5.8 and 6.3 GHz, respectively. The measured bandwidths of the four bands are 1.2%, 2%, 1.9% and 0.9%. The minor discrepancy (frequency shifts) is mainly attributed to the fabrication errors.

Figs. 10(a)-(d) show the simulated and measured radiation patterns in E-plane at 4.6, 5.05, 5.8 and 6.3 GHz, respectively. As can be seen, measured and simulated results agree well with each other, showing

using a single-mode patch antenna. The methodology and design process are detailed with the study of the parameters. The four frequency bands can be adjusted by changing the coupling strength between the resonators. In addition, the operation bands can be adjusted without changing the shape of the antenna, providing a flexible method in antenna design. Simulated and measured results show that the proposed antenna has very good impedance matching and radiation performance at the four distinct frequency bands. This paper provides a novel method to achieve multiband antenna based on circuit methods. The antenna can also be further developed to dual-polarized antennas and high gain array antennas.

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similar uni-directional radiation patterns and very low cross polarization level. At the four frequencies, the radiation pattern achieve a XPD lower than - 30 dB in $\theta = 0^0$ and the front-back ratio is better than 10 dB. Fig. 11 shows the simulated and measured antenna gain from
4.0 to 7.0 GHz. As can be observed, the proposed antenna has four peak gain points at 4.6, 5.05, 5.8 and 6.3 GHz, respectively.

V. Conclusion

A new multiband uni-directional antenna utilizing a network of coupled resonators is introduced in this paper. This design incorporates a resonant network that enables the operation across multiple frequency bands can be achieved by

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