Design Approach for a Microstrip Yagi Antenna With a Switched Beam Using Resonant \( \text{TM}_{10} \) and \( \text{TM}_{20} \) Modes

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ABSTRACT In this paper, a design approach for a microstrip Yagi antenna with a switched beam using resonant \( \text{TM}_{10} \) and \( \text{TM}_{20} \) modes is proposed. The antenna consists of a driven patch and two parasitic patches. Initially, a driven patch radiator with two symmetric probes is investigated to determine whether \( \text{TM}_{10} \) or \( \text{TM}_{20} \) mode of this patch can be generated by properly exciting the dual feeding ports. The operating bands of the dual modes are reallocated in close proximity to overlap with each other by introducing the shorting pins and narrow slots. Then, two smaller-sized parasitic patches are placed on the right side of the driver to achieve switchable tilted-beam radiation patterns. The results demonstrate that the smaller-sized parasitic patches act as either directors or reflectors when their \( \text{TM}_{10} \) mode or \( \text{TM}_{20} \) mode is excited, respectively. Therefore, the quasi-end-fire beams can be satisfactorily generated and steered in the E-plane by switching these two radiative modes by feeding probes. Finally, a proposed antenna is designed and measured. The measured results show that the antenna operating in \( \text{TM}_{10} \) and \( \text{TM}_{20} \) modes can achieve a common band of 3.03–3.19 GHz, and their beams are oriented at the directions of \(+27^\circ\) and \(-42^\circ\) in E-plane patterns, respectively. Most importantly, no RF switches are introduced in our design, thus significantly reducing the complexity and cost of the proposed antenna.

INDEX TERMS Microstrip Yagi antenna, switched-beam antenna, resonant modes, two ports, quasi-end-fire beam.

I. INTRODUCTION

Recently, the demand for high-speed and high-quality data transmission has increased greatly with the development of wireless communication systems. However, the data rate drops dramatically as the transmission distance increases due to the multipath fading. Antennas with switchable beams are well-known solutions used to overcome this problem.

A series of antennas that focus on switched beams have been proposed [1]–[4]. Generally, monopole and dipole antennas are the two forms used as switched-beam antenna elements [1], [2]. Slot antennas are also a simple form used to realize beam switching [3], [4]. In addition, various patch antennas that make use of different radiating modes to achieve beam switching have been proposed [5], [6]. Although all of the abovementioned antennas could achieve beam switching, they could not obtain tilted beams. Nevertheless, antennas with tilted beams are in high demand in some detection applications, including airborne, missile and in-vehicle systems.

Based on the above requirements, many types of antennas with switchable tilted beams have been proposed [7]–[10]. For example, in [7], a phased array antenna with wide-angle scanning performances in E plane was achieved. As reported in [8], a multi-beam antenna based on butler matrix was proposed, the tilted beam was achieved by utilizing the form of a Yagi antenna. In addition, the reconfigurable partially...
reflective surface was used to realize switchable tilted beams in [9], [10]. Nevertheless, the above-mentioned antennas suffered from complex feeding network, large volume or multiple elements, which will increase the cost and complexity of the antennas significantly.

Recently, some reconfigurable microstrip Yagi antennas with switched beams were proposed and improved, as reported in [11]–[18]. The microstrip Yagi antenna has the well-known advantages of low profile, low cost and easy integration. Meanwhile, it can provide a tilted beam without any complex feeding network so it is suitable for realizing switched-beam performance. Typically, as depicted in [11]–[15], the radiation beam of the antenna could be discretely switched by changing the state of the pin diodes installed on the parasitic elements. Instead of discrete beam switching, continuous beam scanning was achieved through the varactors as reported in [16]–[18]. Nevertheless, diodes or varactors are always required for all of these antennas to control the states of these parasitic elements. Unfortunately, the introduced RF components increase the losses and complexities because of the additional DC biasing network. In addition, the parasitic patches should be placed on the both side of the driven element to switch the beams, thus increasing the surface area of the antenna dramatically.

In our work, a novel approach to design a microstrip Yagi antenna with a switched beam using resonant TM$_{10}$ and TM$_{20}$ modes is proposed. As far as we know, this is the first time that the concept of multimode has been introduced into the switched-beam microstrip Yagi antenna. First, a driven patch radiator is excited by two symmetric ports to excite two independent radiative modes, i.e., TM$_{10}$ and TM$_{20}$ modes, with different input powers. Then, a few shorting pins and slots are introduced underneath this driven patch to move the operating bands of these dual modes to overlap with each other. Finally, the other two parasitic patches with smaller sizes are placed on the right side of the driven patch to generate the tilted-beam pattern. The results show that these parasitic patches act as directors or reflectors when their TM$_{10}$ mode or TM$_{20}$ mode is excited, respectively. By switching these two modes, two different states of quasi-end-fire beams along the $+x$-axis and $-x$-axis can be successfully generated for the antenna in E-plane radiation patterns. It is worth mentioning that the parasitic elements only need to be placed on the one side of the driven element instead of on the both sides and the surface area of the radiating patches is reduced to 0.45 $\lambda_0^2$.

II. ANTENNA DESIGN

A. ANTENNA CONFIGURATION

Fig. 1 shows the structure and detailed dimensions of the proposed microstrip Yagi antenna. It consists of three radiating patches (a driven patch and two parasitic patches), a TP-2 dielectric substrate ($\varepsilon_r = 3.5$, $\tan \delta = 0.001$ and $H = 3.5$ mm), and a ground plane. To excite TM$_{10}$ and TM$_{20}$ modes separately, two symmetrical ports are utilized to feed the driven patch. In addition, an array of shorting pins with a radius of 0.7 mm is installed underneath each radiator, and four linear slots with a width of 2 mm are etched on these patches. The main target herein is to reallocate the inherent resonant frequencies of these two modes to overlap with each other. In this context, a commercial ANSYS high-frequency structure simulator (HFSS) is used to simulate and design the proposed antenna.

B. OPERATING PRINCIPLE

To illustrate the working principle of the switched-beam ability of our proposed antenna in detail, Fig. 2 illustrates the design evolution of the proposed microstrip Yagi antenna, which mainly consists of four steps. As studied in [19], for a microstrip Yagi antenna operating in TM$_{10}$ mode, the parasitic patch can act as a director if its size is slightly smaller than that of the driven patch. Meanwhile, to obtain the quasi-end-fire beam, the distance $d$ between two adjacent patches should be kept at approximately 0.2 $\sim$ 0.45 $\lambda_{10}$ ($\lambda_{10}$ is the free space wavelength at TM$_{10}$ mode). As a result, $\varepsilon_r$ of the substrate should be chosen rigorously in a range of 1.5 to 5. As shown in Fig. 2 (a), if the value of $\varepsilon_r = 3.5$ is selected herein and two smaller-sized parasitic elements are placed on the right side of the driver, the main beam of the antenna in $xoy$-plane tends to be oriented towards the positive $x$-axis direction. However, for a microstrip Yagi antenna working in TM$_{20}$ mode in Fig. 2 (b), the smaller-sized parasitic patch could actually act as a reflector, and the value of $d$ should be selected to be approximately 0.2 $\sim$ 0.45 $\lambda_{20}$ ($\lambda_{20}$ is the free space wavelength at TM$_{20}$ mode) to achieve the quasi-end-fire beam. To reach it, $\varepsilon_r$ needs to be designated as large as possible, e.g., approximately 10.2 in [20], to reduce the size of the patch resonator effectively. Hence, the results in Fig. 2(b) depict that the antenna in TM$_{20}$ mode can indeed maintain the maximum beam towards the negative $x$-axis since the parasitic patches behave as reflectors.

Based on the above discussion, we can conclude that the beam-switchable performance in the $\pm x$-axis direction can be realized by switching TM$_{10}$ and TM$_{20}$ modes of the
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A switched-beam microstrip antenna is proposed, which utilizes a patch radiator on a single-layer substrate. Unfortunately, three unavoidable issues need to be addressed. First, if $\varepsilon_r = 3.5$ is selected and employed for the antenna to realize $+x$-axis end-fire radiation in the $\text{TM}_{10}$ mode, the distance $d$ becomes extremely larger than $0.45\lambda_{10}$ under its $\text{TM}_{20}$ mode. As such, the equal amplitude of two radiation beams on the left side in Fig. 2(c) is unsuitable for the $-x$-axis end-fire radiation. Second, the resonant frequencies of these two modes are kept far away from each other, thus being unable to be excited in the overlapping working bands. Third, the feeding port is critical because we need to excite one mode while suppressing the other mode at the same time if we want to switch the two modes.

To address these critical issues, an array of four linear slots is properly etched on each radiating patch, as depicted in Fig. 2(d), to reduce the resonant frequency ($f_{20}$) of its $\text{TM}_{20}$ mode with a slight effect on the resonant frequency ($f_{10}$) of its mode. Meanwhile, a set of eight shorting pins is installed between the radiating patch and ground plane to increase $f_{10}$ dramatically with a slight influence on $f_{20}$. To achieve the minimum frequency ratio ($f_{20}/f_{10}$), the locations of these slots and pins need to be properly selected around the nodal lines of electric fields of its $\text{TM}_{20}$ mode, as demonstrated in [21], [22]. In addition, $f_{20}$ will be reduced eventually in this process and the values of $d/\lambda_{10}$ and $d/\lambda_{20}$ will be both adjusted gently to the range of $0.15 - 0.45$.

Next, two feeding ports are utilized herein to switch and isolate these two modes instead of a single port. When the two ports are excited with the same amplitude and out of phase, a virtual electric wall can be perfectly established in the symmetrical plane ABCD (the symmetrical plane refers to the plane which passes through the centerline AB of the driven patch and is perpendicular to the driven patch) for the microstrip patch antenna. It is well known that for the odd-order $\text{TM}_{10}$ mode of the patch antenna, the ABCD plane becomes a perfect electric wall. In contrast, for the even-order $\text{TM}_{20}$ mode, the ABCD plane must act as a perfect magnetic wall. Therefore, only the odd mode ($\text{TM}_{10}$ mode) is successfully excited to achieve the $+x$-axis end-fire beam. In contrast, when the two ports are excited with equal amplitude but in phase, a virtual magnetic wall can be perfectly established in the symmetrical plane of the microstrip patch antenna. Based on the above discussion, only the even mode ($\text{TM}_{10}$ mode) is successfully excited to achieve the $-x$-axis end-fire beam. With these arrangements, the beam-switchable performance in $\pm x$-axis can be successfully obtained as presented in Fig. 2(d).

To further illustrate the above working principle in detail, the current distributions of the two different modes at 3.05 GHz marked with red arrows are plotted in Fig. 3. It should be mentioned that 3.05 GHz represents the central frequency of the presented antenna, i.e., the overlapping frequencies in the simulation for the two modes. As shown in Fig. 3(a), if the two ports are excited out of phase, the current is in phase along the $+x$-axis for a patch element, and the
TM₁₀ mode of the patch antenna is accordingly excited. It can be seen herein that the first parasitic patch is located close to the driver to induce a stronger current. Hence, the directive characteristic is mainly determined by the first parasitic patch. Most importantly, the currents on the driven patch and first parasitic patch both flow along the positive x-axis direction and nearly in phase, thus acting as a director in this condition. Fig. 3 (b) shows the surface current distributions of the antenna excited with equal amplitude but in phase. It can be seen that the current is out of phase for a patch element at TM₂₀ mode. Similarly, the reflective function is almost determined by the first parasitic patch. However, the currents on the driven patch and first parasitic patch are almost out of phase, which is different from that of TM₁₀ mode. As a result, the current on the parasitic patch is ahead of that on the driven patch, thus acting as a reflector.

C. PARAMETRIC STUDIES

In this section, the resonant and radiative performances of the proposed antenna are investigated and discussed to assess effective switched-beam capability through vital parameters in Fig. 1. It should be noted that only one parameter is studied in each round, with the other parameters unchanged, as shown in Fig. 1.

1) RESONANT PERFORMANCE: REDUCTION OF F₂₀

First, let us investigate the influence of the etched slots on two resonant frequencies of the antenna (f₁₀ and f₂₀); the relevant results are presented in Fig. 4. Note that only one radiating patch (driven patch) is investigated herein. It can be observed that f₂₀/f₁₀ decreases at first and then increases slowly. In addition, the lowest f₂₀/f₁₀ is regularly attained under the selection of Xₙ₁/L₀ = 0.6 with different Lₙ₁/W₀. Based on this tendency, the value of Xₙ₁/L₀ is finally chosen as 0.60 to achieve the small frequency ratio f₂₀/f₁₀. Most importantly, the longer slot acquires the smaller f₂₀/f₁₀, and the minimum f₂₀/f₁₀ is reduced to approximately 1.65 as Lₙ₁ reaches approximately 11 mm (Lₙ₁/W₀ = 0.31).

2) RESONANT PERFORMANCE: INCREMENT OF F₁₀

Considering that the two modes of the antenna are still kept far away from each other by loading four slots, the additional shorting pins are then installed between the radiating patch and ground plane to improve f₁₀ rapidly with a slight influence of f₂₀. Fig. 5 depicts the frequency ratio as a function of Xₚ/L₀ for the 1-element antenna loaded with two pins, four pins or eight pins. It is observed herein that f₂₀/f₁₀ is decreased rapidly when the values of Xₚ/L₀ increase from 0.2 to 0.7, and a minimum f₂₀/f₁₀ can be obtained at Xₚ = 0.7L₀. Afterwards, the values of f₂₀/f₁₀ tend to be unchanged. Therefore, Xₚ = 0.7L₀ should eventually be selected to obtain a small frequency ratio. Meanwhile, f₂₀/f₁₀ decreases as the pin number increases from 2 to 8 at Xₚ/L₀ = 0.7. Finally, f₂₀/f₁₀ is successfully reduced to approximately 1.0 as the number of loaded pins reaches 8.

3) RADIATIVE PERFORMANCE

Next, let us investigate the influence of the shorting pins and slots on the radiation performance of the antenna. To simply analyse this tendency, a 2-element (a driven patch and a parasitic patch) microstrip antenna is studied and discussed. Figs. 6(a) and (b) show the configurations of the antennas without/with additional loaded pins and slots for comparison, respectively. Note that the spacing between the centres of the dual radiating patch is kept at d = 41.75 mm.

Table 1 and Fig. 7 illustrate the resonant frequencies and radiation patterns of the antenna in two different cases. Case 1: λ₁₀/d = 0.25 and λ₂₀/d = 0.49 are obtained for the conventional antenna, leading to a large frequency ratio f₂₀/f₁₀ of approximately 2. Hence, only the quasi-end-fire beam of its TM₁₀ mode is acquired for the antenna. In contrast, the radiation pattern of its TM₂₀ mode maintains two
maximum beams, as shown in Fig. 7 (a). Case 2: $\lambda_{10}/d = \lambda_{20}/d = 0.42$ is satisfactorily attained by introducing the shorting pins and slots, and the far-zone radiation patterns in Fig. 7(b) depict that both of its TM$_{10}$ and TM$_{20}$ modes simultaneously generate tilted-beam patterns. It should be mentioned that the beam angle can be adjusted by some key parameters of the antenna, e.g., the sizes of the parasitic elements, the number of radiating elements and the size of the ground, as demonstrated in [23]. It is believed that the expected beam angle can be acquired if the above parameters can be chosen reasonably. The detailed analysis is omitted in our work because the main target herein is to obtain the switched patterns by exciting two types of radiative modes of the microstrip patch antenna.

Furthermore, the final $f_{10}$ and $f_{20}$ should be finely adjusted by the values of $L_s$ and $Y_p$ to ensure that $\lambda_{10}/d$ and $\lambda_{20}/d$ appear in a range of 0.2 - 0.45, while $X_p$ and $X_s$ have been confirmed. In our design, $L_s = 11$ mm and $Y_p = 4$ mm are selected. To date, all vital parameters with regard to the shorting pins and slots have been determined and discussed.

In our design, $L_s = 11$ mm and $Y_p = 4$ mm are selected. To date, all vital parameters with regard to the shorting pins and slots have been determined and discussed. However, to reduce the complexity and size of the antenna, only three main radiating patches are finally chosen in our design.

**III. MEASURED RESULTS**

To validate the theoretical predicted performances, a prototype of the 3-element antenna is finally fabricated, and its photograph is shown in Fig. 8. It should be mentioned that more elements can further improve the performance of the antenna, but we only utilize three elements here to reduce the complexity and size of the antenna. In our measurement, the two port S-parameters of the proposed antenna with two physical single-ended ports, i.e., $S_{11}$, $S_{12}$, $S_{21}$, and $S_{22}$, are measured with an R&S ZNB-20 vector network analyser. Herein, the $|S_{dd11}|$ or $|S_{cc11}|$ of this proposed antenna can be calculated by using $0.5 \times (S_{11} - S_{12} - S_{21} + S_{22})$ and $0.5 \times (S_{11} + S_{12} + S_{21} + S_{22})$, respectively. The isolation between the two ports $|S_{dc}|$ of this proposed antenna is also calculated by using $0.5 \times (S_{11} + S_{12} - S_{21} - S_{22})$ according to the literature [24], and the relevant results are presented in Fig. 9. The measured overlapping frequencies of the antenna ranges from 3.03 to 3.19 GHz (5.1%), which are in good agreement with the simulated values. This result also shows that both of

![Figure 6](image-url)  
**FIGURE 6.** Configurations of the 2-element dual-mode patch antennas. (a) Case 1: without loaded pins and slots. (b) Case 2: with loaded pins and slots.

![Figure 7](image-url)  
**FIGURE 7.** Simulated radiation patterns of the 2-element dual-mode patch antennas in the xoz plane. (a) Case 1. (b) Case 2.

![Figure 8](image-url)  
**FIGURE 8.** Photograph of the fabricated 3-element microstrip Yagi antenna.

![Figure 9](image-url)  
**FIGURE 9.** Simulated and measured $|S_{dd11}|$, $|S_{cc11}|$, and $|S_{dc}|$ of the proposed antenna.
TABLE 2. Comparison of Some Exciting Switched-Beam Microstrip Yagi Antennas and Our Work.

| Refs | Center frequency GHz | Bandwidth % | Number of switches | Number of patches | Radiating patches area ($\lambda^2$) | Gain (dBi)  |
|------|----------------------|-------------|--------------------|------------------|-----------------------------------|-------------|
| 11   | 5.88                 | 12          | 5                  | 0.58             | 6.4–8.8                           |
| 12   | 9.65                 | 24          | 5                  | 1.2              | 8.9–10.1                          |
| 14   | 2.38                 | 4           | 5                  | 0.96             | 7.0–8.0                           |
| 16   | 2.45                 | 16          | 5                  | 1.04             | 8.6–11.2                          |
| 17   | 3.40                 | 8           | 4                  | 0.28             | 4.3–7.3                           |
| This work | 3.11              | 0          | 3                  | 0.45             | 6.7–7.5                           |

FIGURE 10. Schematic of the 3 dB hybrid coupler.

FIGURE 11. Simulated and measured radiation patterns at the central frequency (3.11 GHz). (a) TM$_{10}$ mode at $\phi = 0^\circ$ and $\theta \in [0^\circ, 360^\circ]$. (b) TM$_{10}$ mode at $\theta = 27^\circ$, $\phi \in [0^\circ, 360^\circ]$. (c) TM$_{20}$ mode at $\phi = 0^\circ$ and $\theta \in [0^\circ, 360^\circ]$. (d) TM$_{20}$ mode at $\theta = -42^\circ$, $\phi \in [0^\circ, 360^\circ]$.

the simulated and measured isolations are kept above 15 dB over the entire frequency band.

In addition, the radiation patterns of the proposed antenna are measured by using a SATIMO near-field measurement system. The 3 dB hybrid coupler shown in Fig. 10 is employed. In this context, the two feeding ports of the antenna are connected to port-3 and port-4 of the hybrid coupler. In this way, port-1 and port-2 can produce differential and common signals, respectively. As a result, TM$_{10}$ and TM$_{20}$ modes of the antenna can be excited by switching port-1 and port-2, thus generating two states of radiation patterns. Fig. 11 plots the far-zone radiation patterns of the proposed antenna under two different modes. The simulated and measured patterns are in good agreement. As port-1 is excited, the main beam of the antenna is radiated towards the $x$-axis direction. In contrast, as port-2 is excited, the maximum value of the radiation pattern is kept in the $-x$-axis direction. As a result, the dual tilted angles of the peak beams deviating from the $z$-axis are $+27^\circ$ and $-42^\circ$. Meanwhile, the measured gains at the central frequency of these two modes reach approximately 7.5 dBi and 6.7 dBi.

To further indicate the novelty of our structure, a comparison between our proposed antenna and some reported switched-beam microstrip Yagi antennas is provided as shown in Table 2. It can be seen that all the previous works required switches (diodes, varactors or MEMS switches). Compared with [11] and [14], we obtained a considerable gain but the area of our antenna was smaller. Although the antennas in [12] and [16] obtained higher gains than ours, too many switches are introduced and the areas are significantly enlarged. Therefore, the antenna in our work achieves several attractive performances, inclusive of compact size, simple structure as compared to these previous works.

IV. CONCLUSION

In this paper, a novel design approach for a beam-switchable microstrip Yagi antenna under the operation of TM$_{10}$ or TM$_{20}$ modes is presented. First, the working principle of the beam switchability is extensively investigated. The results demonstrate that TM$_{10}$ and TM$_{20}$ modes of the patch antenna can be simultaneously generated by switching these two modes, resulting in generating the maximum beams from the $+x$-axis to the $-x$-axis. In addition, a few shorting pins and slots are loaded on each patch, which can not only reallocate the two modes in resonance to overlap with each other but also adjust the electrical length between two adjacent patches. As such, the quasi-end-fire patterns are satisfactorily acquired. Next, a dual-port feeding scheme is employed to excite these dual modes freely. Finally, the proposed antenna is designed, fabricated, and tested. The measured results show that the antenna has realized beam-switchable performance oriented at $27^\circ$ to $-42^\circ$ while maintaining attractive advantages such as low profile, low cost, and simple structure.
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