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# A Novel HF Broadband Frequency-Reconfigurable Whip Antenna With Radiation Blades Loading

**HENGFENG WANG, CHAO LIU, XU XIE, (Member, IEEE), AND HUANING WU**
College of Electronic Engineering, Naval University of Engineering, Wuhan 430033, China

Corresponding author: Hengfeng Wang (henvin999@163.com)

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**ABSTRACT** Aiming at the problems of low gain, low efficiency in low frequency band and warping pattern in high frequency band of the existing HF broadband whip antenna, this paper introduces frequency reconfigurable antenna technology and radiation blades loading technology to redesign whip structure, loading and matching network in different bands, and designs a kind of frequency-reconfigurable whip antenna with improved gain and efficiency. The whip body structure, loading and matching network structure of the antenna in each band are optimized, and the on-off control is carried out through the radio frequency switch according to the actual needs. The results show that the standing wave ratio of the proposed antenna is all less than 3, the average value is 2.32; the gain is all greater than -2dB, the average value is 3.63dB; the total efficiency is all over 20%, the average value is 72.77%, and the pattern keeps horizontal omnidirectional in the whole short wave band without upward warping phenomenon.

**INDEX TERMS** Frequency-reconfigurable technology, radiation blades loading, broadband antenna, lumped loading, matching network, grasshopper optimization algorithm.

## I. INTRODUCTION

The working frequency band of 10-meters HF whip antenna is 3$\sim$30MHz, and the bandwidth is up to 10 octaves. In the whole short-wave band, for the whip antenna with standing wave current distribution, the limitation of its operating frequency band is mainly caused by its impedance characteristics [1], [2], because the input impedance of whip antenna is highly sensitive to frequency, which is hard to match the feeder. In low frequency band, the antenna has small electrical length, small input resistance, large input capacitance, high Q value, low antenna efficiency, narrow working frequency band, which makes it difficult to meet the requirements of modern communication. In high frequency band, the effective length of antenna is far larger than 1/4 wavelength, the reverse phase current on the oscillator increases continuously, the maximum direction of the antenna pattern deviates from the horizontal direction, and the phenomenon of "warping" appears, which results in the antenna can't satisfy the short-range and medium-range communication in the high frequency band. In order to improve the bandwidth and radiation performance of antennas, top loading [3], [4], loading network [5]–[7], broadband matching network [8]–[10], fractal technology [11]–[13] have been proposed. At present, loading and matching network technology is widely used, because the introduction of impedance elements effectively improves the standing wave of antenna, but it also brings new losses to the antenna, which greatly reduces its gain and efficiency. Paper [14] optimize the design of loading and matching network for whip antenna in the whole short wave, and achieves good bandwidth. However, it is obvious that the gain and efficiency of the antenna in the low frequency band and the pattern in the high frequency band are discarded, so the whole short wave band can't be well considered at the same time. For this wide band antenna, the impedance matching is usually achieved by sacrificing gain and efficiency, which is difficult to ensure that the antenna has good radiation characteristics in the whole short-wave band. In order to effectively improve the problems of low gain, low efficiency in low frequency band and warping pattern in high frequency band of 10 m HF broadband whip antenna, it is necessary to solve the contradiction between lower antenna height in low frequency band and excessive antenna height in high frequency band.

For a wideband whip antenna with a certain height, the effective height needs to be increased in the low frequency band, while the effective height needs to be reduced in the high frequency band. The emergence of frequency

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reconfiguration technology [15]–[20] undoubtedly provides a way to solve this problem. According to the radiation characteristics of the antenna, the band of the antenna is reasonably divided, and a radiator structure, loading and matching network scheme is designed and optimized for each band of the antenna. The antenna has better bandwidth and radiation characteristics under each band through real-time switching by the radio frequency switch according to the actual needs.

In order to design more efficient reconfigurable antenna improving the radiation performance, the second section of this paper will discuss the principle of radiation blade structure, study and analyze the influence of radiation blade structure on antenna performance, and then design a best structure of radiation blades, the third section will redesign and optimize each band of reconfigurable antenna, the fourth section will verify and analyze the reconfigurable antenna experimentally, the fifth section will summarize this paper.

## II. RADIATION BLADES STRUCTURE

The current distribution of traditional whip antenna is not uniform. The higher the antenna is, the smaller the current is, the current reaching the top of the antenna is almost zero, and the radiation ability of the antenna is greatly reduced. Therefore, from the angle of top loading, we can change the whip structure of the upper part of the antenna with multilayer radiation blades, which can increase the current of the upper part of the antenna, and make the current distribution of the antenna more uniform, so that it can improve the effective height of the antenna and enhance the radiation ability, which provides an effective method to solve the gain and efficiency defect of the whip antenna in low frequency band.

### A. STRUCTURE PRINCIPLE OF ANTENNA RADIATION BLADES

When the radiation blade is loaded on the whip antenna body, the distributed capacitance between each radiation blade to the ground can be equivalent to a transmission line respectively, the superposition of multi-segment equivalent transmission lines is the total equivalent transmission lines when the antenna loads multi-layer radiation blades, which brings stronger current and higher radiation resistance to the upper part of the antenna. As shown in Figure. 1, if the height of the $i$-th radiation blade is $h_i$, the capacitance between $i$-th blade to the ground is $C_i$, and the characteristic impedance of the vertical line segment is $Z_{0i}$, the increase in effective length of antenna by the $i$-th radiation blade is $h_i$', which can be calculated as follows [21]:

$$Z_{0i} \cot kh_i' = \frac{1}{\omega C_i} \tag{1}$$

$$h_i' = \frac{1}{k} \arctan (Z_{0i} \omega C_i) \tag{2}$$

where k is wavenumber, $\omega$ is angular frequency, and the characteristic impedance of a single vertical conductor is

$$Z_{0i} = 60 \left( \ln \frac{2h_i}{a} - 1 \right) \Omega \tag{3}$$

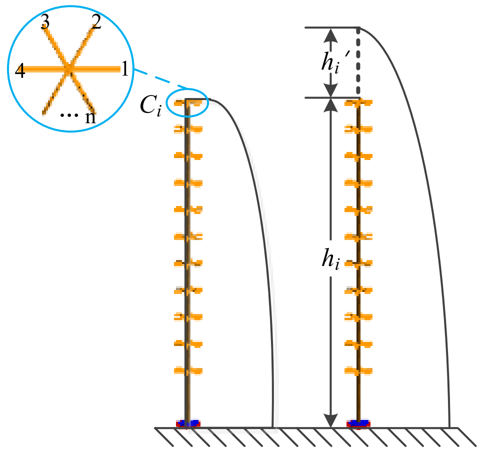



**FIGURE 1. Current distribution of radiation blade loaded antenna.**

where $h_i$ is the height of the vertical part and $a$ is the radius of the conductor. After the above transformation, the multi-layer radiation blades loaded antenna can be regarded as a $h_0 = h + h' = h + \sum_i h_i'$ high unloaded antenna, $h$ is the actual height of the antenna, $h'$ is the sum increase in effective length of antenna by all radiation blades.

Let the current distribution on the antenna be

$$I_z = I_0 \frac{\sin \left[ k \left( h + h' - z \right) \right]}{\sin \left[ k \left( h + h' \right) \right]} \tag{4}$$

where $z$ is the distance from a point on the antenna to the input port, $I_0$ is the input current, so the effective height is

$$\begin{aligned} h_e &= \frac{1}{I_0} \int_0^h I_z \mathrm{d}z = \frac{2 \sin \left( k \frac{h+2h'}{2} \right) \sin \frac{kh}{2}}{k \sin \left[ k \left( h + h' \right) \right]} \\ &= \frac{2 \sin \left( k \frac{h + 2 \sum_i h_i'}{2} \right) \sin \frac{kh}{2}}{k \sin \left[ k \left( h + \sum_i h_i' \right) \right]} \end{aligned} \tag{5}$$

When $\left( h + h' \right) / \lambda$ is very small, the formula can be simplified to

$$h_e \approx \frac{h}{2} \left( 1 + \frac{h'}{h + h'} \right) \tag{6}$$

Obviously, the effective height of the antenna after adding multi-layer radiation blades is larger than that of the antenna without radiation blades, which increases the effective height of the antenna without increasing the actual height of the antenna, and provides an effective method to improve the radiation resistance and efficiency of the antenna.

### B. RADIATION BLADES STRUCTURE ANALYSIS

In order to reduce the complexity of the antenna, further simplify the structure and effectively reduce the number of radiation blades, it is necessary to discuss and analyze the influence of the distribution of antenna radiation blades on

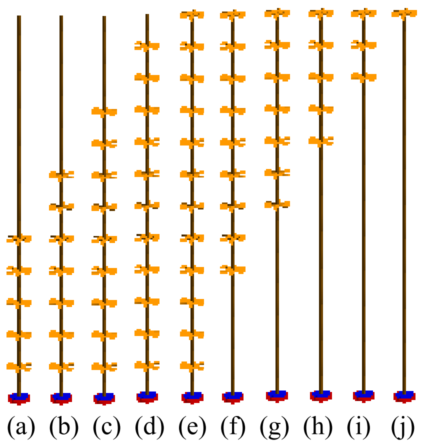
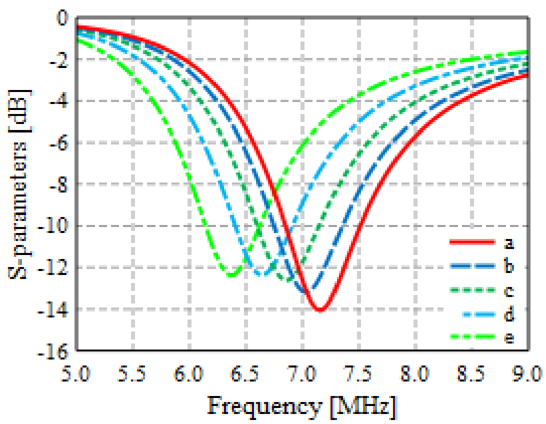
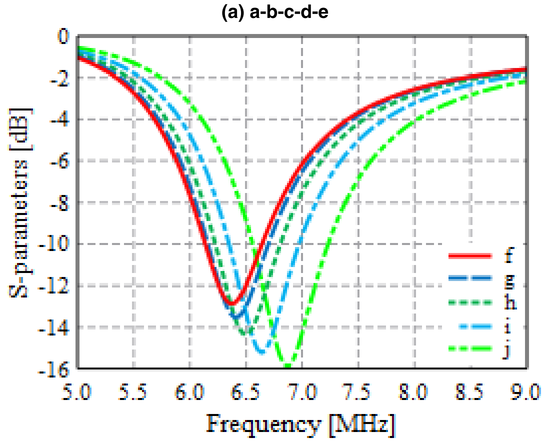



**FIGURE 2.** Structure of antenna radiation blades under different distribution.




(a) a-b-c-d-e




(b) f-g-h-i-j

**FIGURE 3.** S11 curves under different radiation blades distribution.

antenna radiation characteristics, respectively setting the distribution structure of the radiation blades of the antenna as shown in Figure. 2, and the S11 curves of the antenna under the different distribution of the radiation blades are obtained as shown in Figure. 3 through simulation calculation.

It can be seen that the resonant frequency becomes smallest when 12 layers radiation blades are uniformly distributed. When the radiation blades is concentrated on the upper part of the antenna body, the resonant frequency of the antenna can get a smaller value. Removing the radiation blades of the upper part of the antenna body has a great impact on the antenna performances, while removing the radiation blades of the lower part of the antenna body has a very small impact, so what mainly reduces the resonant frequency of the antenna is the radiation blades of upper part of the antenna. Adding radiation blades not only makes the current at the top of the antenna not zero, but also improves the current distribution in the upper and middle segments, which makes little contribution to the current distribution in the lower segment of the antenna. The main contribution to improving the current distribution of the antenna lies in the upper radiation blades, not the lower radiation blades. Therefore, in the actual design of the antenna, emphasis should be placed on setting the radiation blades in the upper part of the antenna.

### C. STRUCTURAL DESIGN OF RADIATION BLADE

As shown in Figure. 4, a 10-meter whip antenna model is built in FEKO software. Ten radiation blades are added to the upper part of antenna, each layer is 50 cm apart and evenly distributed in the upper part of antenna. Each radiation blade contains 6 branches, each branch length is 40 cm, and the radius is set to 1 cm.

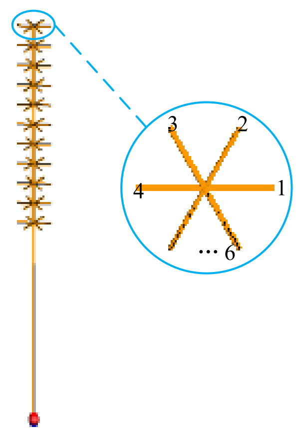
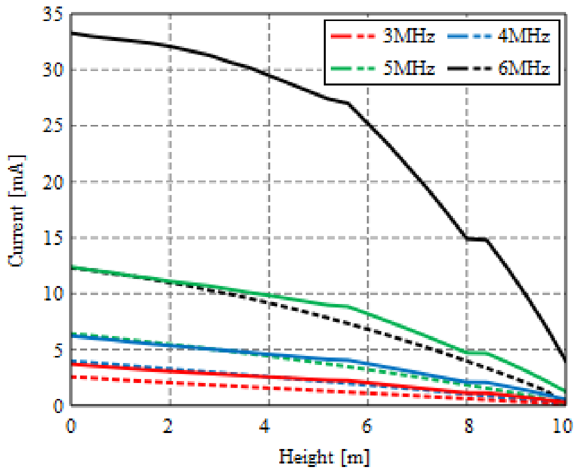
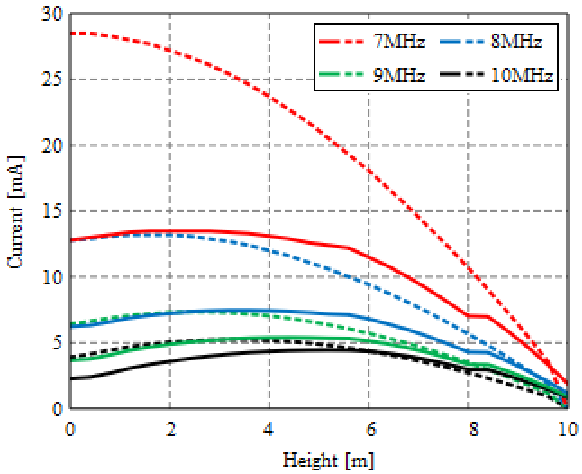



**FIGURE 4.** Radiation blades structure of the proposed antenna.

The current distribution of 10-meter antenna loaded with radiation blades in low frequency band is shown in Figure. 5. The current on the antenna decreases with the increase of the antenna height. Even when it reaches the top of the antenna, the current is not zero, which obviously improves the defect of the traditional antenna that the current on the top of the antenna is zero. When the frequency is low, the current of the radiation blades loaded antenna is obviously larger than that of the traditional antenna. When the frequency is higher than 6.5MHz, the current distribution of the radiation blades loaded antenna will gradually be less advantageous than that of the traditional antenna. The input impedance of the 10-meter antenna loaded with radiation blade is shown in Figure. 6. After adding radiation blades, the input resistance




(a) 3∼6MHz




(b) 7∼10MHz

**FIGURE 5.** Antenna current distribution (solid line for radiation blade structure, dotted line for single whip structure).

of the antenna in low frequency band increases and the capacitance impedance decreases, which will greatly improve the radiation performance of the antenna and realize the impedance matching between the antenna and the feeder. Therefore, the improvement of the current distribution of the antenna in low frequency band by radiation blades loading is very obvious.

### *D. SCALING MODEL TESTING*

In order to better verify the effectiveness of the radiation blades structure, a 10:1 scale model is designed for the whole antenna. According to the structure of antenna radiation blades in Figure. 4, 10 layers of radiation blades are arranged for the antenna, each layer is 5 cm apart, mainly distributed in the upper part of the antenna. Each radiation blade contains 6 branches, each of which has a length of 4 cm and a radius of 1 mm. Figure 7 is a scaling model of a 1-meter whip antenna loaded with radiation blades. The frequency range is 30-300 MHz and the frequency interval is 10 MHz. The S11 parameters of the antenna measured by a vector network analyzer are shown in Figure 8.

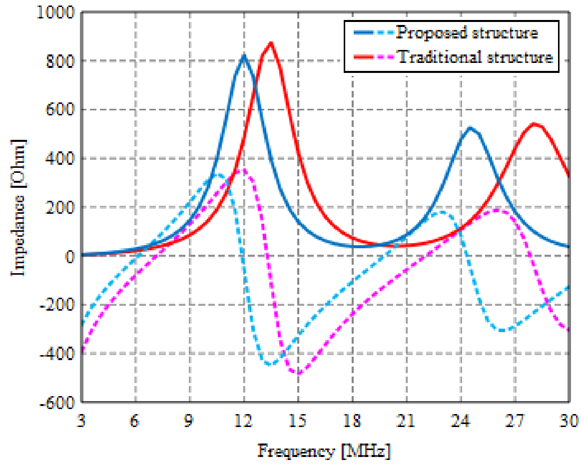



**FIGURE 6.** Antenna input impedance (solid line for real part, dashed line for imaginary part).

**FIGURE 7.** Scaling model of traditional antenna and proposed antenna.

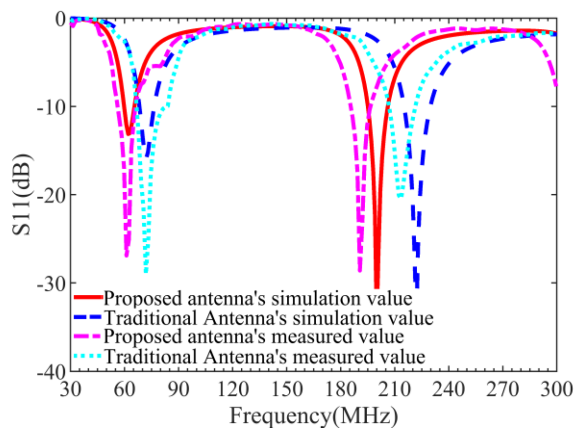



**FIGURE 8.** S11 curves of traditional antenna and proposed antenna.

From Figure. 8, it can be seen that the resonant point of the radiation blades loaded antenna in the low frequency band is 61MHz, while that of the traditional antenna in 72MHz. The radiation blades structure reduces the resonant frequency of the 1m whip antenna by 11MHz, which is equivalent to increasing the effective height of the antenna by 0.19m, greatly increasing the input resistance of the antenna, reducing the capacitive reactance. Additionally, it is beneficial to improve the radiation performance of the antenna and to match the antenna with the feeder so that effectively broadening the working frequency band of the antenna. The test results are in good agreement with the simulation results, and slightly better than the simulation results.

## III. DESIGN OF FREQUENCY RECONFIGURABLE ANTENNA

The object of this paper is a 10-meter whip antenna. In low frequency band, the height of antenna is far less than a quarter wavelength, the radiation resistance of antenna is very small and the capacitance is very large. Generally, the impedance matching is realized by loading impedance elements to reduce the standing wave ratio, but the introduction of resistance elements leads to low gain and low efficiency of antenna. In high frequency band, the height is far greater than a quarter of the wavelength, and the reverse phase current gradually appears on the antenna arm. With the increasing frequency, the maximum direction of the antenna pattern deviates from the horizontal direction, and the phenomenon of upward warping appears, which is not suitable for short-and medium-range communication. Therefore, the short-wave band can be divided into three bands: band I (3-5MHz), band II (5-15MHz) and band III (15-30MHz). Based on the principle of high performance and miniaturization, this paper configures different whip structure, loading and matching network design for each band on a pair of antennas, and makes real-time selection through radio frequency switch.

### A. ALGORITHM OPTIMIZATION

In order to achieve impedance matching effectively, different loading and matching networks are designed for each band. Therefore, it is necessary to use efficient algorithms to optimize the parameters of loading and matching networks for achieving the desired design purposes. This paper will introduce a new algorithm simulating grasshopper swarm behavior, Grasshopper Optimization Algorithms (GOA), which was proposed by S Seyedali in 2017 and inspired by locust lifestyle [21], [22]. The algorithm simulates grasshopper behavior more comprehensively, and is an optimization algorithm based on its social interaction. Because of its simple algorithm, no gradient mechanism, effective avoidance of falling into local optimum and the mechanism of treating the problem as a black box, it has been applied in many scientific research and engineering design [23], [24]. The main optimization process of GOA is shown in Figure 9.

GOA is used to optimize the parameters of the loading network and broadband matching network of the antenna. The gain of the antenna is improved on the premise that the VSWR of as many frequency points as possible is less than 3. For loading network, the objective function of optimization calculation is to minimize the maximum VSWR and maximize the minimum gain of each sampling frequency point in the band.

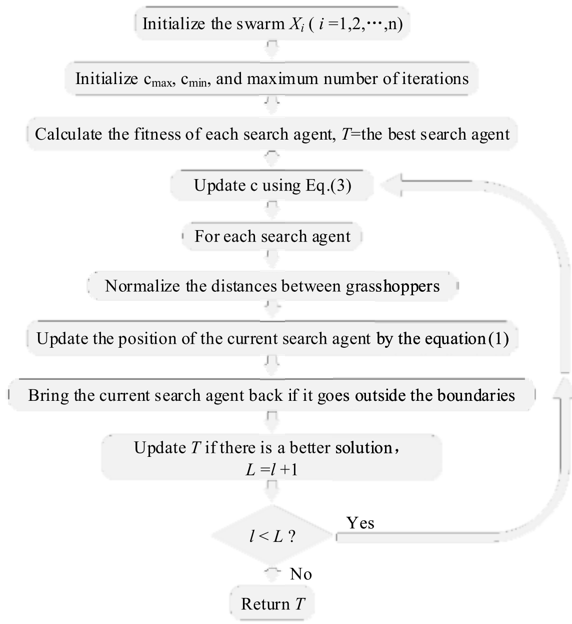



**FIGURE 9. Flow chart of the GOA.**

$$F = \min\{\sum_{i=1}^{n}[W_i(VSWR(\omega_i) - 1)^2 + A_i(G_0 - G(\omega_i))]\} \quad (7)$$

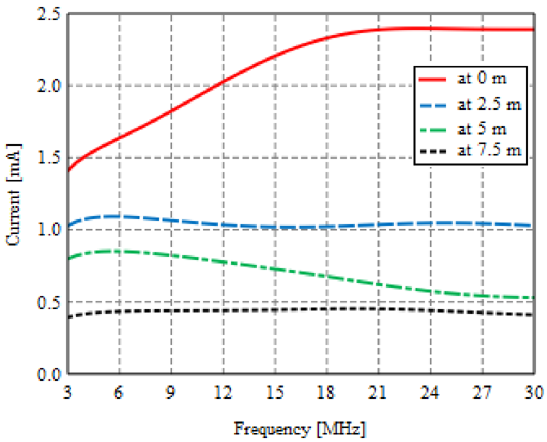
where $G(\omega_i)$ is the gain of antenna at $\omega_i$, $G_0$ is rated gain, which is an adjusting parameter to weigh the broadband impedance characteristics and gain characteristics of antenna. $W_i$ is the weighted value of VSWR at each frequency point, whose value depends on the relative importance of $VSWR(\omega_i)$. On the one hand, it retains a good VSWR, on the other hand, it discards a bad VSWR. Obviously, the smaller the value of the objective function, the better the optimization effect.

The objective function of the matching network should minimize the average VSWR in the frequency band.

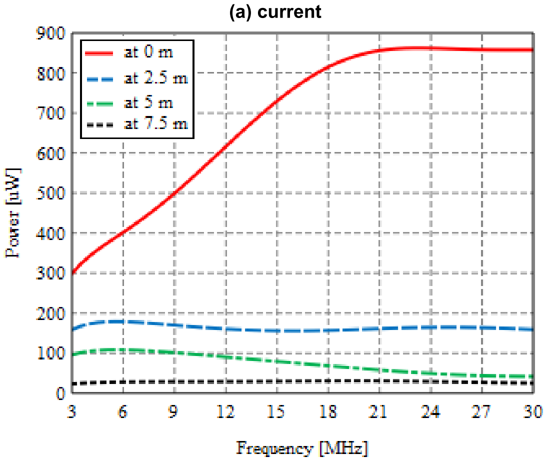
$$F = \min[\frac{1}{n}\sum_{i=1}^{n} VSWR(\omega_i)] \quad (8)$$

### B. STRUCTURAL ANALYSIS

The emphasis of this paper is to improve the gain and efficiency of low frequency band and to solve the problem of high frequency pattern warping. Reactance loading can improve the efficiency of antenna, but the bandwidth is narrow. Resistance loading can effectively reduce the standing wave ratio of antenna and expand the bandwidth, but the efficiency is low. Therefore, the influence of the number and position of resistance loading on the antenna needs to be analyzed. In FEKO, the radiation blades loaded antenna model as shown in Figure 4 is established, the same resistance is loaded at 0 m, 2.5 m, 5 m and 7.5 m of the antenna respectively. The current and loss power on each resistance are shown in Figure 10. Because the current distribution on the antenna decreases gradually from the bottom to the top, and the loss power of



(a) current



(b) loss power

**FIGURE 10. Current and loss power on loading resistance at different positions of antenna.**

the load resistor on the antenna decreases with the increase of the height. Therefore, the resistance loading of antenna should be placed in the upper part of antenna (especially not on the bottom of the antenna), so as to minimize the loss caused by resistance loading and reduce the loss of antenna efficiency.

### *C. BAND I DESIGN*

The 10-meter whip antenna has a wavelength of 100m at 3MHz, and its height is only 1/10 of the wavelength, far less than 1/4 of the wavelength. The radiation resistance of the antenna in low frequency band is very small, the capacitive reactance is relatively large, and the matching with the feeder impedance is poor, which leads to the narrow bandwidth of the antenna. In order to realize the broadband of the antenna, lumped elements are usually added to the antenna body. The matching of antennas is realized by network and impedance loading, but the gain and efficiency of antennas are greatly reduced. Therefore, the loading structure of radiation blades can be designed for antenna in low frequency band, which will greatly improve the effective height of the antenna, increase the radiation resistance of the antenna, and improve the gain and efficiency of the antenna.

The distribution layers of antenna radiation blades are 10 layers with 50 cm interval, which are mainly distributed in the upper part of the antenna. Each radiation blade contains 6 branches, each with a radius of 1 cm and a length of 40 cm. To further smooth the variation of input impedance with frequency and realize impedance matching between antenna and feeder, a loading network is added at 2.5 meters from the top of antenna body, and a "$\tau$" type of broadband matching network is added at the bottom of antenna, which consists of broadband transmission line transformer and LC network, in which $L_0$ is a adjusting inductance to counteract the high capacitance reactance of antenna, as shown in Figure. 11.

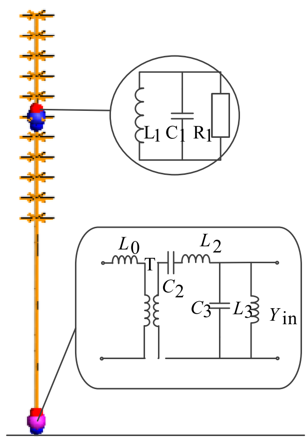



**FIGURE 11. Band I antenna structure.**

**TABLE 1. Optimal values of antenna.**

| R1/ Ω | L1/μ H | C1/p F | L0/μ H | L2/n H | C2/n F | L3/μ H | C3/ nF | T |
|---|---|---|---|---|---|---|---|---|
| 300 | 15 | 20 | 6.8 | 0.47 | 92 | 1.4 | 1 | 2.5 |

The optimized values of each element are shown in Table 1. The optimized results of antenna performance are shown in Figure 12. The voltage standing wave ratio (VSWR) of the proposed antenna is basically less than 3, which is consistent with the trend of traditional antenna. From the input impedance curve of the antenna in Figure. 6, it can be seen that the resistance of the antenna is very small, the capacitance is very large and the rate of change is very large within 3-5MHz. Although band I greatly shortens the frequency range, the adjustment of the input impedance is also limited. A slight sacrifice has been made here to consider the gain and efficiency more. The gain and efficiency of the proposed antenna are significantly greater than those of the traditional antenna, all of which are greater than −2dB. The maximum increase is more than 8dB (from −10.2dB to −2dB at 3MHz). The efficiency of the proposed antenna is all greater than 21% (3% for the traditional antenna), and the improvement of each frequency point is more than 18%.

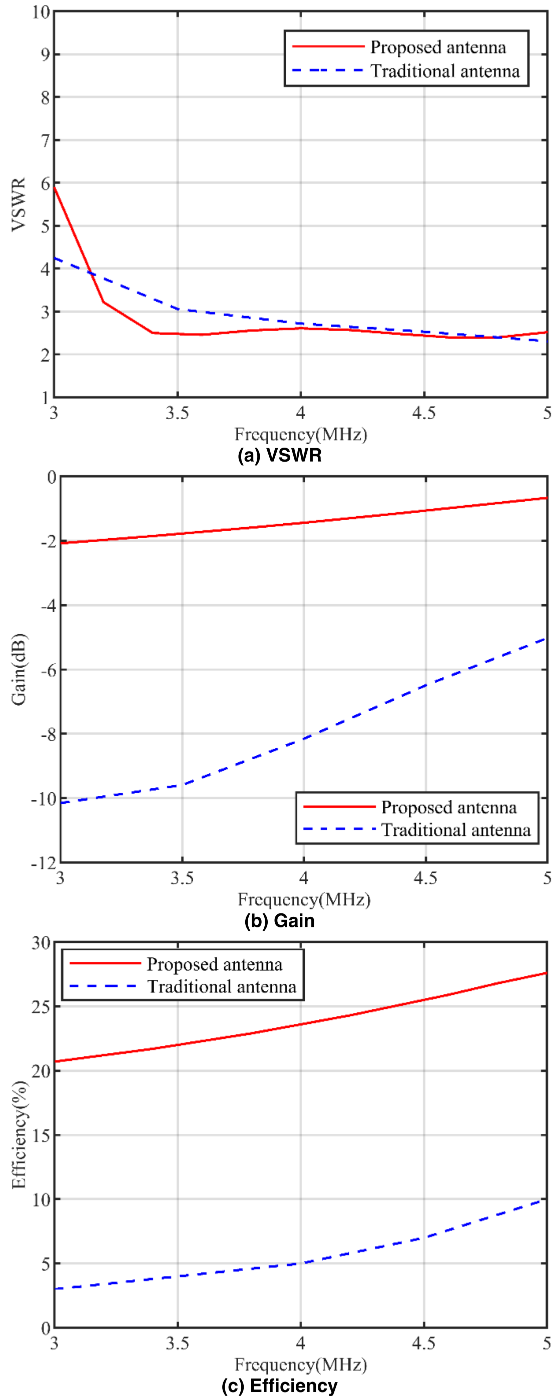



**FIGURE 12.** Characteristic curve of the proposed antenna in band I.

### *D. BAND II DESIGN*

Since the antenna height of 10-meters is within the quarter wavelength range of band II, in order not to add additional complexity to the antenna, this paper will share a set of radiators (including radiator blades structure and impedance loading structure) for band II and band I. Therefore, GOA is only needed to optimize the adjusting inductance $L_0$ and the matching network of the antenna. The optimized values of each element are shown in Table 2 , and the optimized

**TABLE 2.** Optimal values of antenna.

| $R_1$/Ω | $L_1$/μH | $C_1$/pF | $L_0$/μH | $L_2$/nH | $C_2$/nF | $L_3$/μH | $C_3$/pF | T |
|---|---|---|---|---|---|---|---|---|
| 300 | 15 | 20 | 1 | 0.1 | 440 | 2.7 | 85 | 4 |

results of antenna performance are shown in Figure 13. The VSWR of the proposed antenna is less than 3, which is more stable than that of the traditional antenna. The gain and efficiency of the proposed antenna are basically greater than that of the traditional antenna, and the gain is all greater than -0.5dB (-5dB for traditional antenna), and the efficiency is all greater than 28% (10% for traditional antenna).

### *E. BAND III DESIGN*

In band III, the height of the antenna is far greater than a quarter of the wavelength, which results in the maximum direction of the pattern deviating from the horizontal direction and can't be used for short-wave medium and short range communication. Therefore, the height of the antenna in band III should be reduced to prevent the phenomenon of warping in the pattern of the antenna. Considering the stability of the antenna structure and the feasibility of its realization, the radiation height of band III is set to 5 meters which is a quarter wavelength at 15MHz. Therefore, when establishing the antenna model in FEKO, the overall structure of the antenna is retained as shown in Figure 11, and a radio frequency switch is set at the height of 5 meters to control the disconnection of the upper and lower antennas. The timing control circuit can be introduced through the inner cavity in the antenna body. GOA is used to optimize the adjusting inductance $L_0$ and matching network of the antenna. The optimized values of each element are shown in Table 3. The optimized results of antenna performance are shown in Figure 14. The VSWR of the proposed antenna is all less than 3, and the overall distribution is very stable. The gain and efficiency of the proposed antenna are much greater than those of the traditional antenna, all of gain are larger than 4.5dB (0.3dB for traditional antenna) and all of efficiency are more than 94% (32% for traditional antenna). Moreover, the maximum direction of the pattern is still in the horizontal direction, and there is no warping phenomenon. This is because the antenna is disconnected at 5 meters by a RF switch, the antenna only radiates 5 meters below, and the lower part of the antenna radiator has no loss caused by the load resistance, so it achieves good gain and efficiency. The radiation height of the antenna is greatly shortened, which is close to a quarter of the wavelength, so there is no reverse phase current on the arm of the antenna, so that the maximum radiation direction of the antenna is always kept in the horizontal direction.

**TABLE 3.** Optimal values of antenna.

| $R_1$/Ω | $L_1$/μH | $C_1$/pF | $L_0$/μH | $L_2$/nH | $C_2$/pF | $L_3$/nH | $C_3$/pF | T |
|---|---|---|---|---|---|---|---|---|
| 300 | 15 | 20 | - | 125 | 216 | 423 | 52 | 5 |

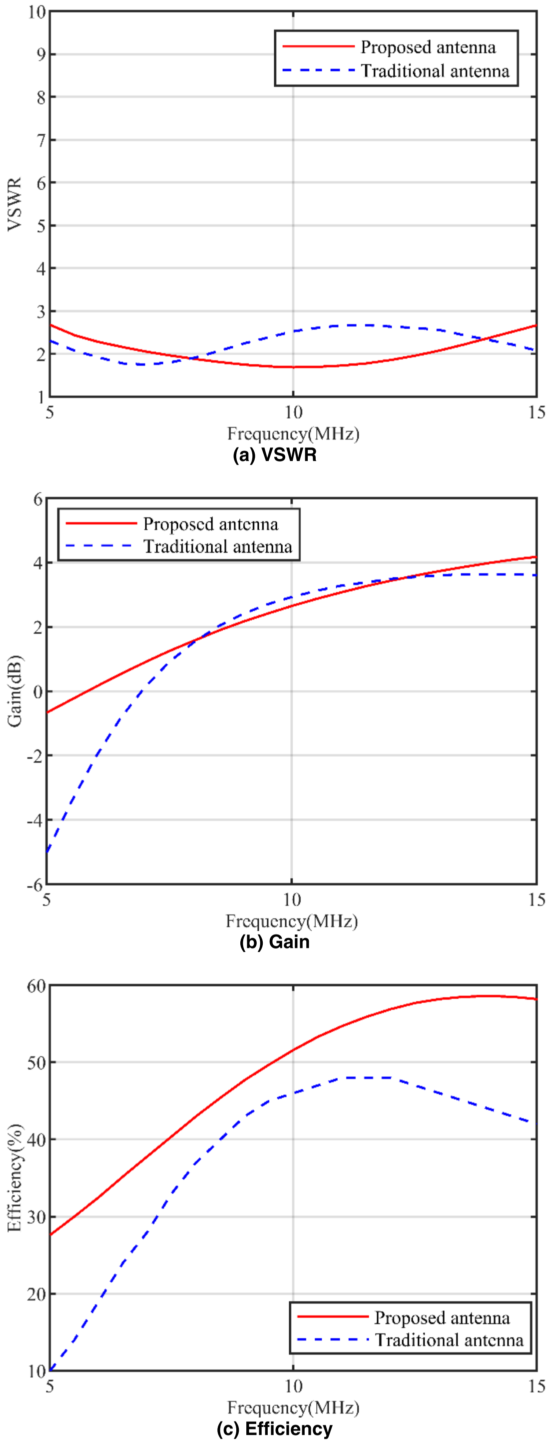



**FIGURE 13.** Characteristic curve of the proposed antenna in band II.

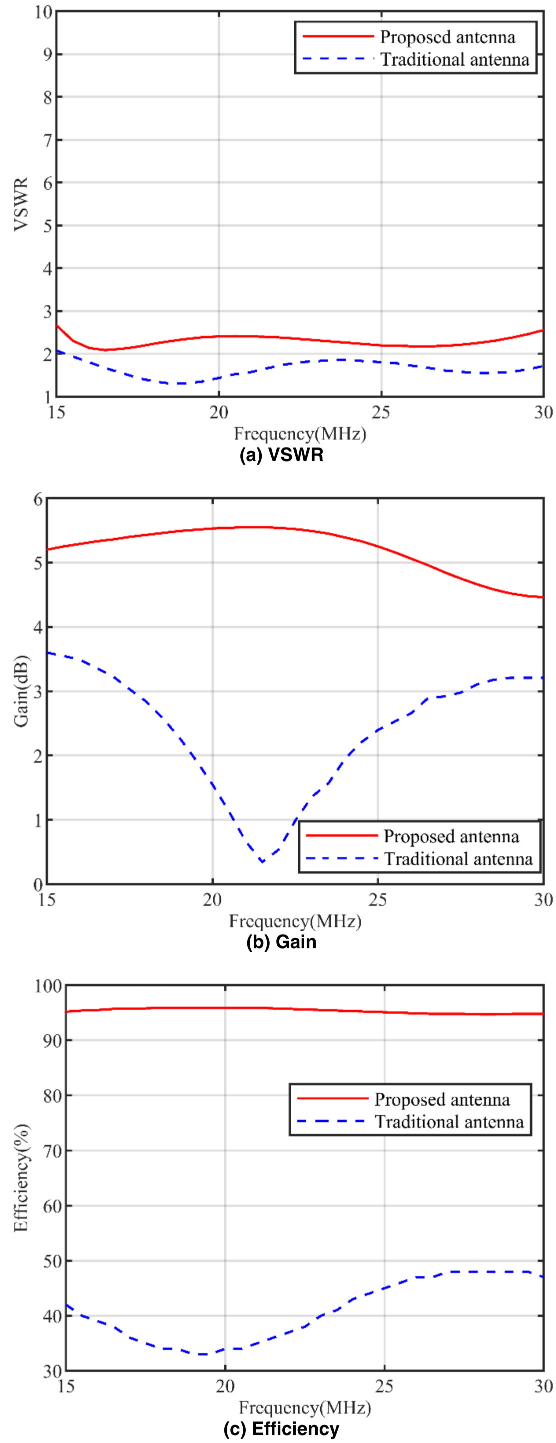



**FIGURE 14.** Characteristic curve of the proposed antenna in band III.

### F. FREQUENCY RECONFIGURABLE DESIGN

The reconfigurable antenna designed in this paper realizes three bands of reconfigurable design in one antenna. Band I and Band II share a common 10 meters radiation whip (including radiation blades structure and impedance loading network). Band III disconnects the upper part of the radiator through the radiator control switch, and only 5 meters at the bottom participates in radiation. At the same time, different adjusting inductances $L_0$ and matching networks are designed for three bands to realize impedance matching between antenna and feeder, and real-time selection is made according to actual frequency by network control switch, seeing in Figure. 15.

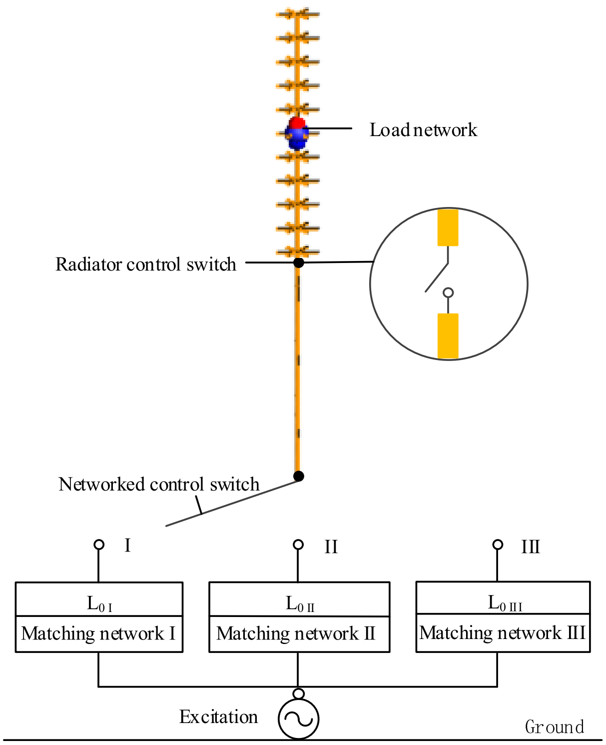



**FIGURE 15.** Frequency reconfigurable antenna structure.

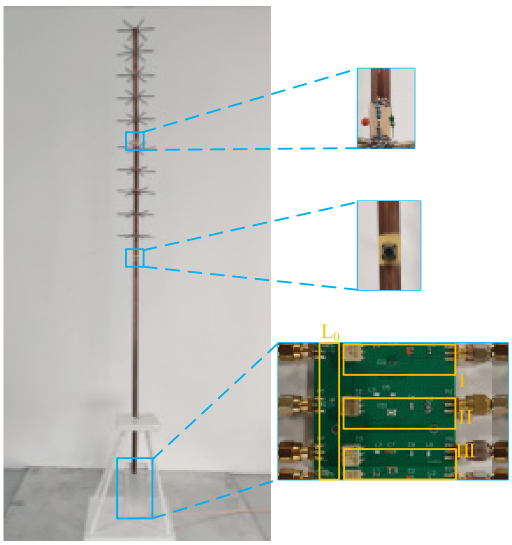



**FIGURE 16.** Proposed antenna scaling model.

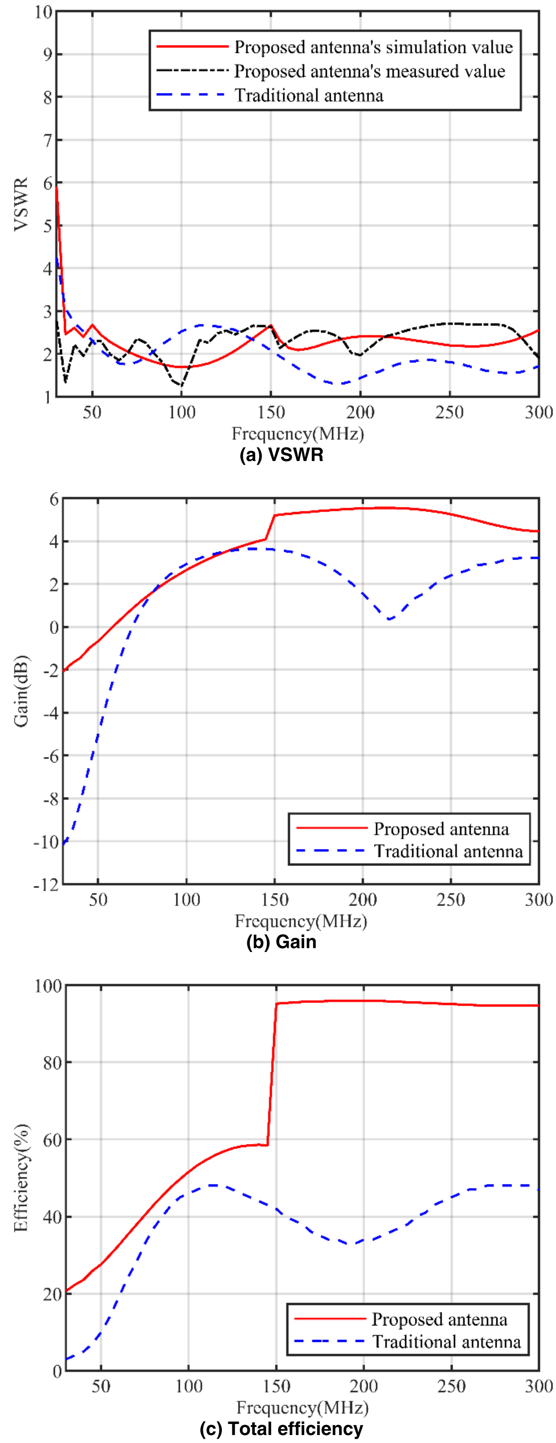



**FIGURE 17.** Frequency reconfigurable antenna characteristic curve.

When the operating frequency is in band I (3-5MHz), the radiator control switch closes, the network control switch switches to port I, and the corresponding adjusting inductance $L_{0I}$ and matching network I are connected to band I. At this time, the reconfigurable antenna is in band I working state; When the operating frequency is in band II (5-15MHz), the radiator control switch keeps closed, the network control switch switches to port II, and access the corresponding adjusting inductance $L_{0II}$ and matching network II of band II. At this time, the reconfigurable antenna is in band II working state; When the operating frequency is in band III (15-30MHz), the radiator control switch is off, the network control switch is switched to port III, and the adjusting inductance $L_{0III}$ and matching network III corresponding to band III are connected. At this time, the reconfigurable antenna is in band III working state. In this way, the proposed reconfigurable antenna realizes the functions of three

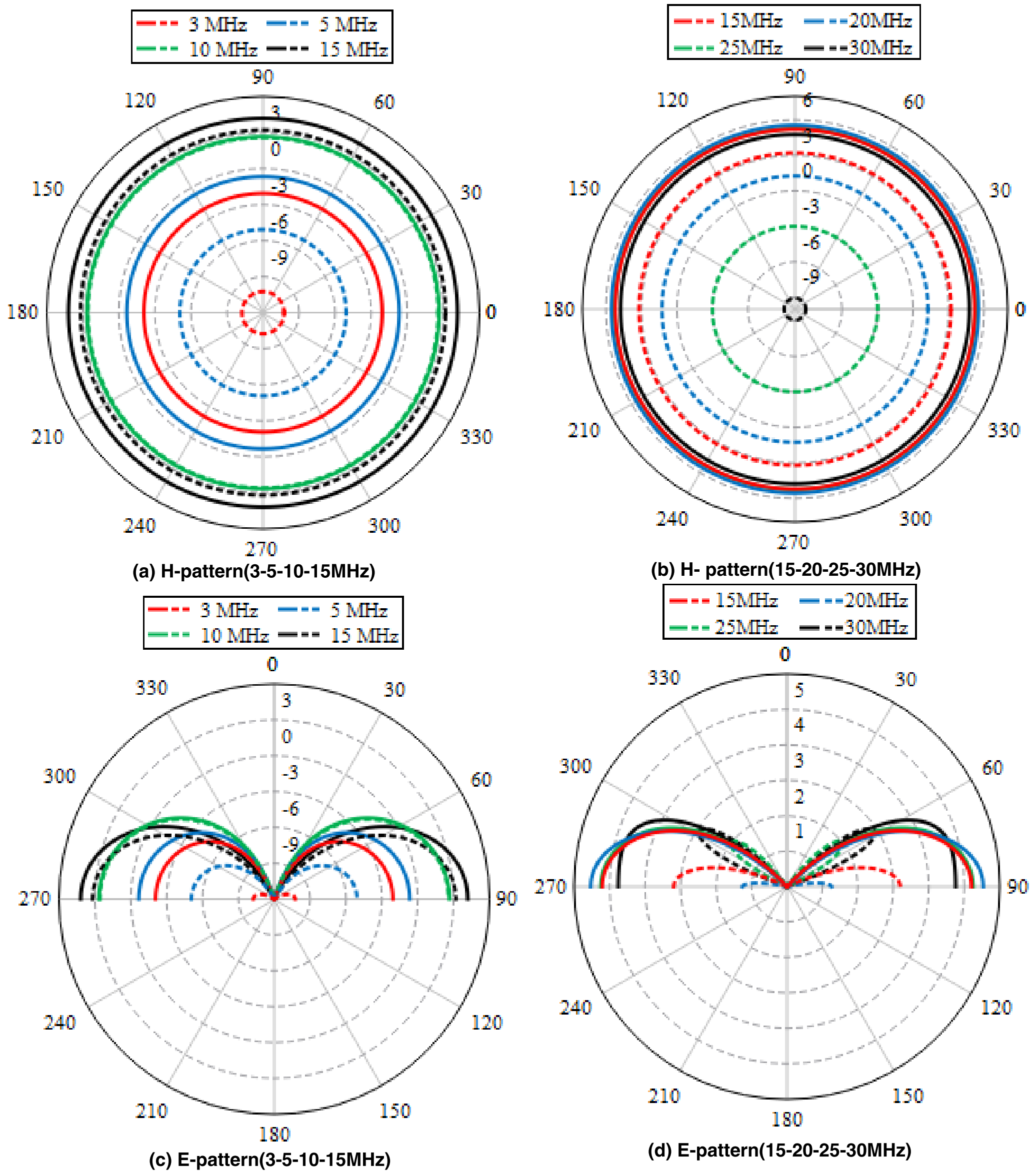



**FIGURE 18.** **Frequency reconfigurable antenna pattern in simulation (solid line for the proposed antenna, dotted line for the traditional antenna).**

antennas on one antenna controlled by radio frequency switches in whole short wave band.

## IV. MEASUREMENT AND ANALYSIS OF SCALED ANTENNA

In order to better verify the effectiveness of the proposed reconfigurable antenna, and considering the possibility of implementation, a simple scale model of 10:1 is made by reducing the overall proportion of the designed antenna, and the electrical parameters of the scale antenna are measured.

According to the structure scheme of Section 3 and Figure. 15, a scaling model of 1-meter reconfigurable whip antenna is established. As shown in Figure. 16, the frequency is set to 30-300 MHz, the frequency interval is set to 10 MHz, the loading points of the upper end of the antenna are shared in three bands, and a mechanical switch is added in the middle of the antenna to control the connection of band I and II and the disconnection of band III, the DC control circuit of the switch enters from the bottom of the antenna and reaches the radiator control switch in the middle of the antenna through the inner cavity of the antenna. In order to simplify the circuit structure, $L_0$ and matching network of each frequency band are integrated into a circuit board. The labels "I", "II", "III" in the figure represent matching network of frequency band I, II and III respectively.

Figure. 17 shows the characteristic curves of the proposed frequency reconfigurable antenna, including VSWR, gain and efficiency. Through the simulation and measurement of the proposed antenna, the simulated VSWR value in 98% of the frequency points is less than 3, the measured value of all the frequency points is less than 3, with an average value of 2.32. The overall trend of the measured value is consistent with the simulation value, but there are some fluctuations under the influence of the environment, and it has been greatly improved in the low frequency band, mainly because of the nonlinearity and loss of the core in the transmission line transformer can smooth the high capacitance reactance at the input end of the antenna in the low frequency band, so that the measured value of the actual antenna in the low frequency band can obtain better standing wave ratio performance. The average gain of the proposed antenna in horizontal direction is 3.63 dB, which is much higher than that of the traditional antenna. The total efficiency of the proposed antenna is more than 20%, and the average is 72.77%, which is much higher than that of the traditional antenna too.

Due to the limitation of size and frequency, it is impossible to measure the far-field radiation pattern of the antenna in the microwave laboratory. Figure 18 shows the pattern of the frequency reconfigurable antenna calculated by the moment method in FEKO simulation, including the horizontal pattern and the vertical pattern. In the whole band, the horizontal pattern of the proposed antenna is omnidirectional, and the vertical pattern is half shape of '$\infty$'. There is no warping phenomenon in the pattern like that of the traditional broadband antenna. Therefore, the frequency reconfigurable antenna designed in this paper achieves omnidirectional radiation with high gain and high efficiency, so that the antenna can meet the requirements of short and medium range communication in the whole band.

The main reason why our antenna has such good gain and efficiency is that: Firstly, the proposed antenna has a small structure of radiation blades for the low frequency band, which improves the effective height of the antenna to a certain extent, improves the input impedance of the antenna, and improves the radiation efficiency. Furthermore, this design only adds a lumped loading point to the antenna, which can make the antenna match well, greatly reduce the power loss caused by loading on the antenna, thus it improves the gain and efficiency of the antenna too. Finally, the band-division design of the antenna reduces the range of the bandwidth, which reduces the difficulty of antenna matching, and also contributes to the improvement of antenna radiation performance.

## V. CONCLUSION

Aiming at the problems of low gain, low efficiency in low frequency band and warping pattern in high frequency band of existing HF broadband whip antenna, this paper introduces frequency reconfigurable antenna technology and radiation blades loading technology to divide the band rationally for whip antenna, and designs different whip structure, loading and matching network structure for each band. According to the actual needs of on-off control, a frequency reconfigurable whip antenna with improved gain and efficiency is designed. The gain of the antenna is all greater than $-2$dB, with an average of 3.63dB; the efficiency is all greater than 20%, with an average of 72.77%, and the pattern is kept omnidirectional in the whole short-wave band without warping. The performance of the whip antenna is obviously better than that of the traditional antenna, which provides an effective method for realizing wideband and high-efficiency of the whip antenna.

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**HENGFENG WANG** received the B.Sc. degree in communication engineering from Hunan University, Changsha, China, in 2014, and the M.Sc. degree in communication and information system from the Naval University of Engineering, Wuhan, China, in 2016, where he is currently pursuing the Ph.D. degree, focusing on shortwave communications, array antenna, and broadband antenna.

**CHAO LIU** received the B.Sc., M.Sc., and Ph.D. degrees in communication engineering from the Xi'an University of Electronic Science and Technology, in 1985, 1996, and 2009, respectively. He is currently a Professor and Ph.D. Supervisor with the College of Electrical Engineering, Naval University of Engineering. His main research interests include VLF communication, antenna design, and numerical analysis for electromagnetic fields.

**XU XIE** received the B.Sc., M.Sc., and Ph.D. degrees in communication engineering from the Huazhong University of Science and Technology, in 1985, 1996, and 2009, respectively. He is currently an Associate Professor and a Master's Tutor with the College of Electrical Engineering, Naval University of Engineering. His main research interests include shortwave communications, array antenna, and radio frequency circuit.

**HUANING WU** received the B.Sc. degree in communication engineering from Nanhua University, Hengyang, China, in 2008, and the M.Sc. and Ph.D. degrees in communication engineering from the Naval University of Engineering, Wuhan, China, in 2010 and 2014, respectively. He is currently a Lecturer of electrical engineering with the Naval University of engineering. His main research interests include shortwave communication and array antenna.