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A Novel Frequency Reconfigurable HF Broadband Whip Antenna Based on GOA Optimization

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Abstract—Aiming at the problems of low gain, low efficiency at lower frequency, and warping in pattern at higher frequency of 10-meter high frequency (HF) whip antenna, the whip antenna is loaded and matched with the network in different bands using Grasshopper Optimization Algorithms (GOA) and antenna reconfiguration technology, so a new frequency reconfigurable broadband whip antenna is designed in this paper. According to the electrical characteristics of the 10-meter HF whip antenna, this paper divides short wave frequency into three bands and designs its radiation structure, loading, and matching network for each band of antenna, respectively. GOA is introduced into the research and design of antenna to optimize component parameters of the loading network and matching network. The results show that the antenna in lower frequency band can be improved at most, the maximum gain growth up to 5.8 dB (from −10.3 dB to −4.5 dB), and the maximum efficiency growth up to 8.5% (from 3% to 11.5%); the gain and efficiency in high frequency band are greatly improved too, and the phenomenon of warping in the pattern is effectively avoided.

1. INTRODUCTION

Whip antenna is a monopole antenna with vertical polarization and omnidirectional pattern in horizontal direction. It has been widely used because of its simple structure, strong texture, and suitable for installation and use on mobile carriers. Due to the wide application of frequency hopping and spread spectrum technology in short-wave communication system, tuned antenna cannot meet the current communication needs, so the wideband of HF whip antenna becomes more and more important [1–4]. Paper [5] designs a dual-loaded broadband whip antenna for shipboard shortwave. The voltage standing wave ratio (VSWR) of the antenna is basically less than 3 : 1, and the average gain in the mid-high frequency band is greater than 2 dB. However, in the low frequency band, the antenna gain is poor, and the lowest is −12 dB. Aiming at the gain deficiency of the antenna in low frequency band, a design scheme of 10-meter reconfigurable HF broadband whip antenna is proposed in this paper by Grasshopper Optimization Algorithms (GOA). The antenna is designed and optimized in different bands by using loading, matching network, and reconfigurable techniques, so that its electrical properties can meet higher requirements in the whole short wave band.

The working frequency band of the 10-meter short wave whip antenna designed in this paper is $3 \sim 30$ MHz, and the bandwidth is very wide, reaching 10 times of the minimum operating frequency. As for the whip antenna with standing wave current distribution in the whole short wave band, the limitation of its operating frequency band is mainly caused by its impedance characteristics, that is to say, the input impedance of the whip antenna is highly sensitive to frequency. Figure 1 shows the impedance characteristics of a 10-meter short-wave whip antenna by FEKO simulation, it can be seen that the impedance characteristics of the whip antenna vary greatly with frequency. Paper [5] optimizes the loading and matching network of the whip antenna in the whole short-wave, and it is obvious that

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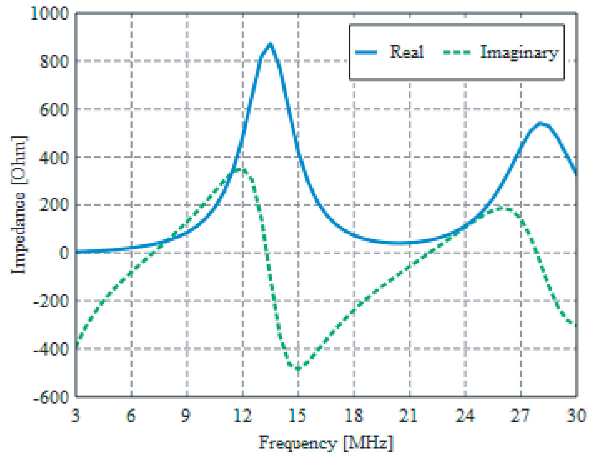


Figure 1. The impedance of 10 m HF whip antenna.

the performance of the low-frequency antenna has some tradeoffs, and the whole short-wave band cannot be taken into account well.

Therefore, in view of this wide-band antenna, it is necessary to carry out a comprehensive analysis based on the results of full-band optimization, rationally divide the bands, and then optimize each band, so that each one corresponds to a set of loading and matching network (with transmission line transformer) structures to ensure better electrical characteristics.

2. GRASSHOPPER OPTIMIZATION ALGORITHM

Natural excitation algorithm has been widely used in scientific research and engineering design because of its simple algorithm, non-gradient mechanism, effective avoidance of falling into local optimum, and the mechanism of treating the problem as a black box [6–11]. In order to optimize the antenna loading and matching network, a new algorithm — GOA, also from the population of nature, is proposed by Saremi et al. in 2017 [12, 13], which is introduced to simulate grasshopper swarm behavior. GOA can simulate grasshoppers' behavior more comprehensively based on their social interaction.

GOA is a kind of natural heuristic algorithm. Its design inspiration comes from the social behavior of grasshoppers in nature. A grasshopper swarm moves slowly in its infancy and has a wide range of activities in its adulthood. These two characteristics make two trends in the search process of natural heuristic algorithm: exploration and exploitation. Exploration and exploitation, as well as target search, are naturally accomplished by grasshoppers. In order to solve optimization problem, paper [12] avoids grasshoppers' reaching comfort zone quickly, and the population does not converge to a specific point. The mathematical model for simulating grasshopper swarm behavior is revised as follows:

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} c\frac{ub_d - lb_d}{2} s\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{d_{ij}}\right) + \widehat{T_d} \tag{1}$$

$$s(r) = fe^{\frac{-r}{l}} - e^{-r} \tag{2}$$

$$c = c_{\max} - \frac{l(c_{\max} - c_{\min})}{L} \tag{3}$$

where X_i^d is defined as the location of the ith grasshopper in the Dth dimension solution space; ub_d and lb_d are the upper and lower bounds of the dimension solution space; $|x_j^d - x_i^d|$ is the distance between the ith grasshopper and jth grasshopper; $(x_j - x_i)/d_{ij}$ is the unit vector of the distance between the ith grasshopper and the jth grasshopper; $s(r)$ is the force function of social activities; f is the attraction intensity between grasshoppers; l is the attraction length between grasshoppers; $\widehat{T_d}$ is the value of the Dth dimension in the target (best solution found so far). c is used to reduce the decline coefficients of comfort zone, exclusion zone, and attraction zone, and $c_{\max}, c_{\min}$ are the maximum and minimum values. l is the current iteration times, and L is the maximum iteration times.

Equation (1) cleverly simulates the interaction between grasshoppers in a swarm. The next position of grasshoppers is determined by their current position, target position, and the position of all other grasshoppers. The first component of the equation takes into account the position of grasshoppers relative to other grasshoppers, and the second component simulates the trend of grasshoppers transferring to food sources, the parameter c simulates the deceleration of grasshoppers approaching food sources and slowing down to eat.

The mathematical model of the GOA requires grasshoppers to move towards the target gradually during the iteration process, avoiding convergence to the target too quickly, so as to fall into local optimum. GOA saves the most promising target in the search space in each iteration and requires grasshoppers to move towards it gradually. This is to find a better and more accurate target as the best approximation of the real global optimum in the search space. Like other evolutionary algorithms, GOA uses fitness function to guide grasshoppers to search their optimal location in D-dimensional space in order to meet the requirements of objective function. At each stage of the algorithm, the position vector corresponding to the optimal fitness value is taken as the global optimal position vector, and this information is transmitted to other grasshoppers around, so that grasshoppers can adjust their steps and position vectors accordingly until they reach the target position of food. The main optimization process of GOA algorithm is shown in Figure 2.

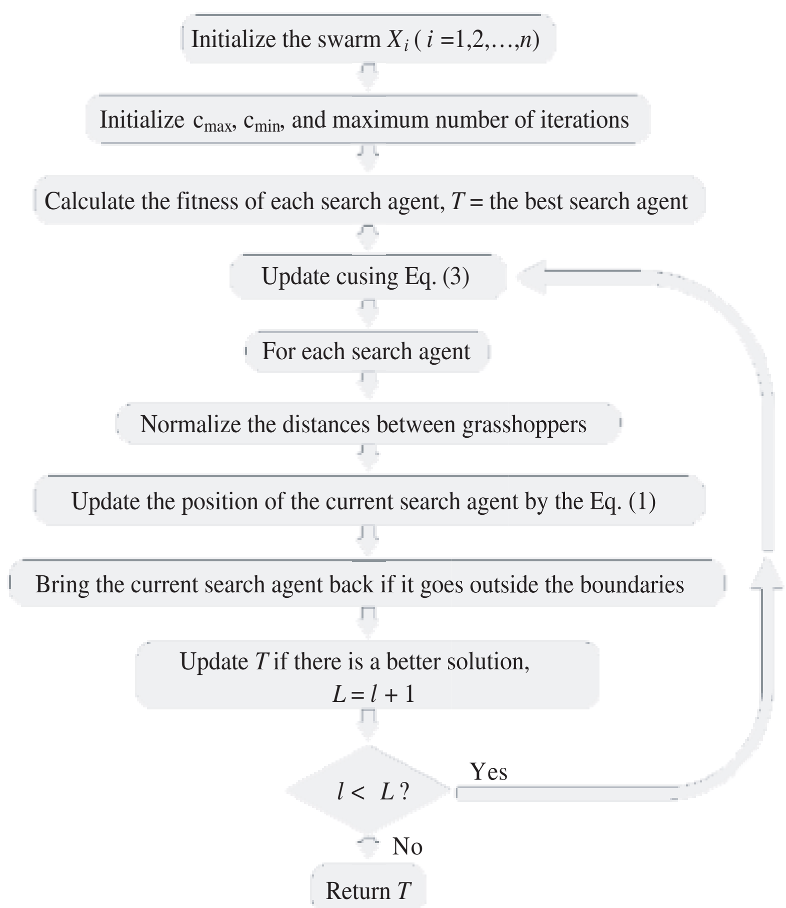


Figure 2. Flow chart of the GOA.

In this paper, GOA is applied to antenna loading optimization and broadband matching network design for the first time. In order to widen the bandwidth of the antenna, this example adds two load networks consisting of RLC parallel connection to the short wave whip antenna [14, 15] and uses GOA to optimize the values of six values load elements, setting $D = 6$, $lb_d = 1$, $ub_d = 1000$, $L = 100$, $N = 0$, and the objective function is as follows:

$$F = \min\left\{\sum_{i=1}^{n}\left[W_i(\,VSWR(\omega_i) - 1) + A_i(G_0 - G(\omega_i))\right]\right\} \tag{4}$$

where $\omega_i(i = 1, 2, \ldots, N)$ is the N-th frequency point; $VSWR(\omega_i)$ and $G(\omega_i)$ refer to the VSWR and gain of the antenna at ω_i; G_0 is a rated gain; A_i is an adjusting parameter; W_i is the weighted value of the VSWR at each frequency point.

After 100 iterations, the grasshopper's optimal trajectory and fitness are shown in Figure 3. Figure 3(a) only lists the locomotion trajectories of the first and second grasshoppers. Figure 3(b) shows the optimal convergence trajectory of the first grasshopper. It can be seen that after 70 iterations, the optimization of the first grasshopper is completed. Figure 3(c) shows the average fitness of all six grasshoppers. It can be seen that after 60 iterations, the GOA optimized antenna loading network has converged. This shows that GOA has fast convergence speed and high convergence accuracy for optimizing an antenna loading network, so it is suitable for the optimization of the proposed antenna.

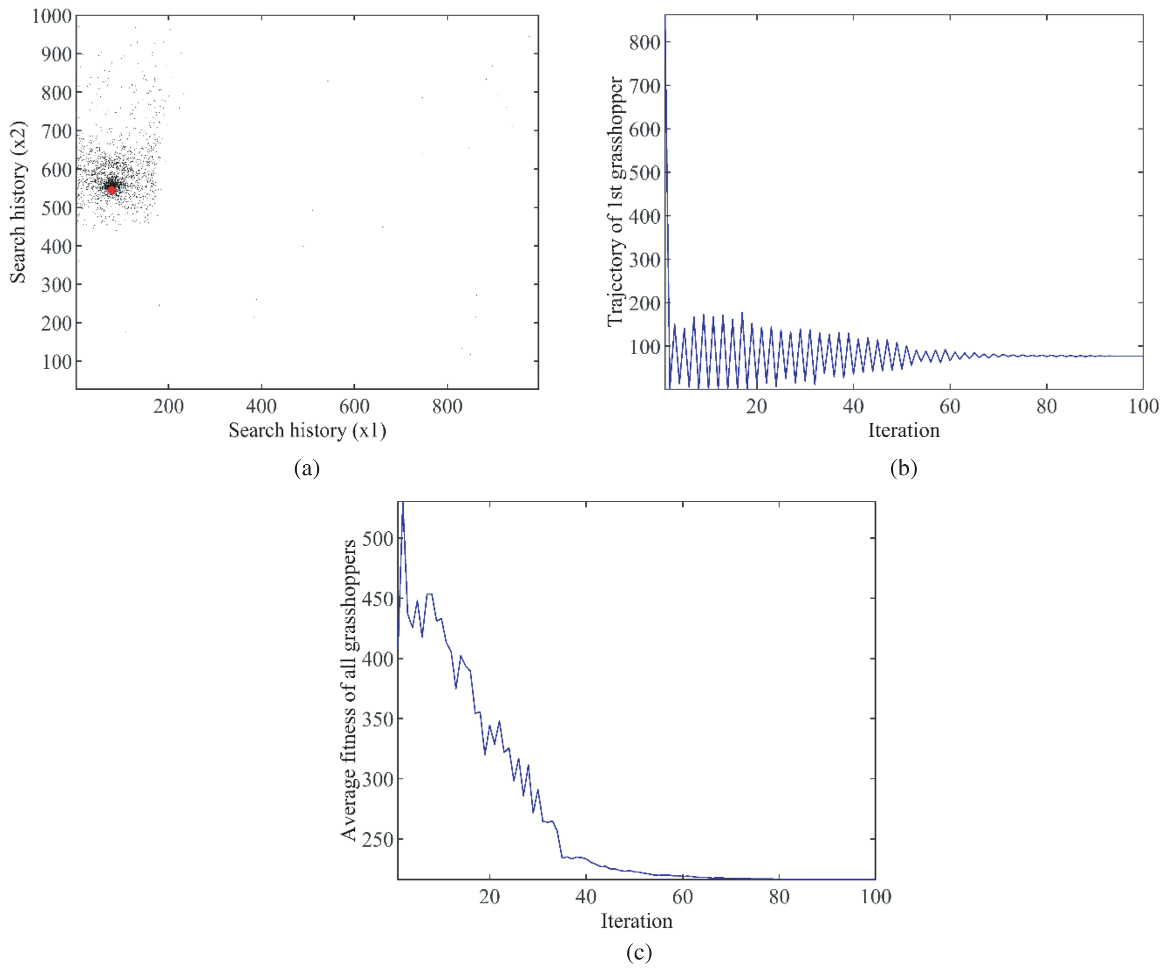


Figure 3. GOA to optimize loading antenna. (a) Optimizing history of the first and second grasshopper (x1 and x2). (b) The trajectory of the first grasshopper (x1). (c) Average fitness of all grasshoppers.

3. ANTENNA DESIGN AND OPTIMIZATION

3.1. Antenna Analysis

At present, the 10-meter whip antenna has a wavelength of 100-meter at 3 MHz, and its height is only 1/10 of the wavelength, far less than 1/4 of the wavelength. However, the wavelength is 10 meters at 30 MHz, and the height of the antenna is equal to the wavelength, far greater than 1/4 of the wavelength. As shown in Figure 1, the antenna has very small radiation resistance and large capacitive reactance in low frequency band, which leads to poor matching with feeder impedance and narrow antenna bandwidth. In order to achieve broadband antenna, an RLC loading network is usually added to the antenna body. Resistance loading broadens the antenna bandwidth but reduces the gain and efficiency of the antenna. The gain of 10 meter HF broadband whip antenna is very low in low frequency band (especially in the range of $3 \sim 6$ MHz), and it is less than -2 dB. The lowest is less than -10 dB, and the variation is very violent.

In the radiation direction of the antenna, the vertical pattern of the antenna is in the half shape of "∞". When the frequency is small, the effective length of the antenna is smaller than the half wavelength, and the current of the dipole arm is in the same phase, seen in Figures 4 and 5. The synthetic field reaches its maximum in the side fire direction ($\theta = 90°$). With the increase of frequency, the effective length of the antenna exceeds half wavelength; the reverse current on the dipole increases from weak to strong; and the side lobes gradually appear. When the effective height equals the wavelength, the reverse current and positive current on the dipole are equal in magnitude, and their fields in the direction of the dipole cancel exactly, so that the direction of the side fire changes from the previous maximum direction to the zero direction. At this time, warping phenomenon appears in the maximum direction of the antenna, thus deviating from the direction of $\theta = 90°$. For a 10-meter whip antenna, when the frequency is greater than 18 MHz, the sidelobes begin to appear in the antenna pattern deviating from the horizontal direction and gradually increase with the increase of frequency, while the main lobes in the horizontal direction gradually decrease. When the frequency increases to 22 MHz, the maximum radiation direction of the antenna begins to deviate from the horizontal direction, which is inclined to a certain angle with the horizontal direction, and increases gradually with the increase of the frequency. The sidelobe in the horizontal direction decreases gradually, that is to say, the antenna pattern is upward warped.

In order to effectively improve low gain, low efficiency in the low frequency band and the pattern warping in the high frequency of the 10-meter HF broadband whip antenna, the contradiction between the low height in the low frequency band and the high height in the high frequency band should be

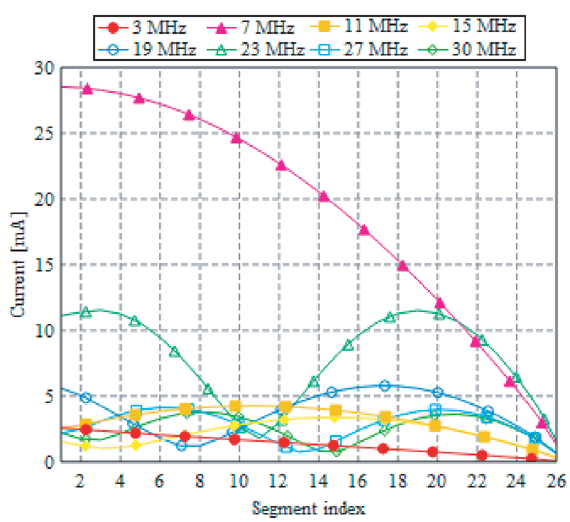


Figure 4. Amplitude change curve of antenna body current at different frequencies.

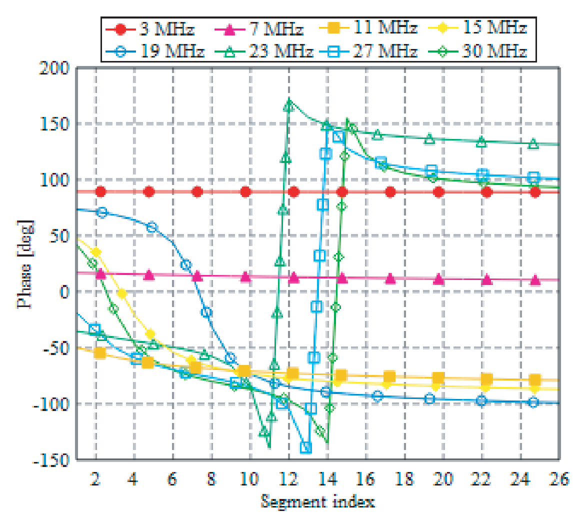


Figure 5. Phase change curve of antenna body current at different frequencies.

solved. It is not feasible to optimize the whole short-wave band to achieve broadband, and the idea of frequency reconfigurable antenna can solve this problem.

3.2. Reconfiguration Antenna Design

The characteristic parameters of the antenna are analyzed one by one after several GOA optimization simulations. Considering comprehensively, $3 \sim 6$ MHz, $6 \sim 18$ MHz and $18 \sim 30$ MHz are divided as three frequency bands of the frequency reconfigurable antenna. In order to minimize the load number, reduce the complexity of the antenna and the difficulty of implementation, and the following factors should be considered in this design [16–19]:

1) Starting from the complexity of antenna structure, there are at most $2 \sim 3$ loading points and $2 \sim 3$ control switches on the antenna body, and the higher the arrangement of the switches are, the more difficult it is to control, so set the control switch at the bottom of the antenna as far as possible.
2) The radiation resistance of low frequency antenna should be increased in band I, and the effective height of antenna should be reduced in band III, so a switch is needed to control the radiation height of the antenna in different frequency bands.
3) From the point of view of the difficulty of antenna realization, the loading points of the upper part of the antenna should be shared as much as possible to reduce the negative impact of structural instability and control signals.

In summary, the reconfigurable antenna [16–19] is designed as follows. The height of the antenna is still 10 meters, and two loading points are set at 7.5 meters and 0 meters of the antenna: Load 1 and Load 2. Three bands share an upper loading point (Load 1). Each band has an independent downloading point: Load 2-1, Load 2-2, and Load 2-3, which is switched by a network controlled switch. In order to take into account band III, a radiator controlled switch is added at 0.5 meters of the antenna. The radiator controlled switch is connected at band I and band II, and the whole radiator participates in radiation, while it is disconnected at band III. Only lower half of the antenna participates in radiation. The structure and working mode of the proposed antenna are shown in Figure 6 and Table 1.

Table 1. The working mode of the proposed antenna.

Frequency band	7.5 m	5 m	0 m
Band I ($3 \sim 6$ MHz)	Load 1	Connect	Load 2-1
Band II ($6 \sim 18$ MHz)	Load 1	Connect	Load 2-2
Band III ($18 \sim 30$ MHz)	Load 1	Disconnect	Load 2-3

3.3. Reconfigurable Antenna Optimization

According to the antenna structure design of Section 3.2, the following optimization is made for band I, band II, and band III, respectively.

The electromagnetic simulation software FEKO establishes a 10-meter whip antenna model. The ground medium chooses an infinite ideal dielectric conductor plane. As shown in Figure 7, two centralized loading points are set on the whip body of the 10-meter antenna, and the upper loading point is set on the upper part of the whip body (25% from the top), adopting the RL parallel loading form. The lower loading point is set on the bottom of the whip body, adopting the RLC parallel adding method. In the form of load, the selection of component parameters for each loading point branch will be determined by GOA. 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.

$$F = \min \left\{ \sum_{i=1}^{n} [W_i(VSWR(\omega_i) - 1)^2 + A_i(G_0 - G(\omega_i))] \right\} \tag{5}$$

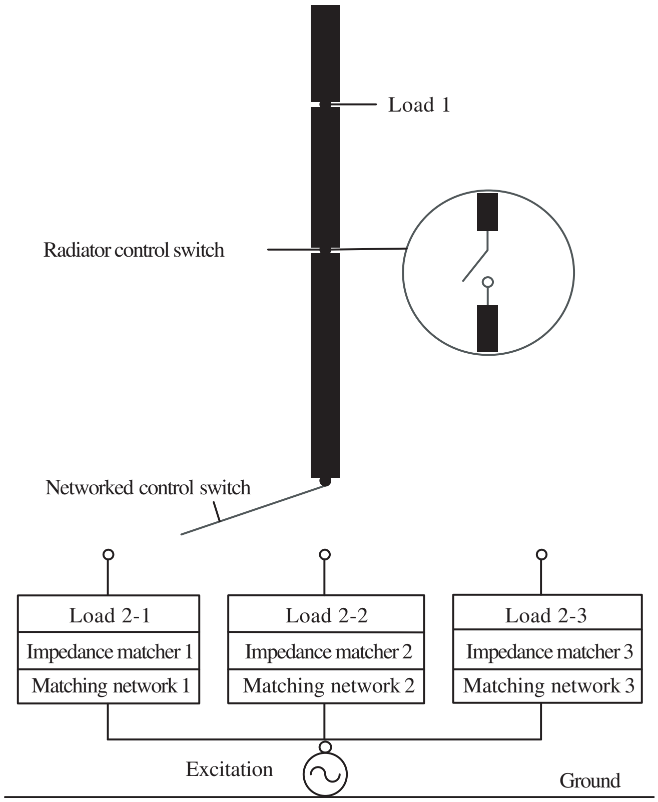


Figure 6. The structure graph of frequency reconfigurable antenna.

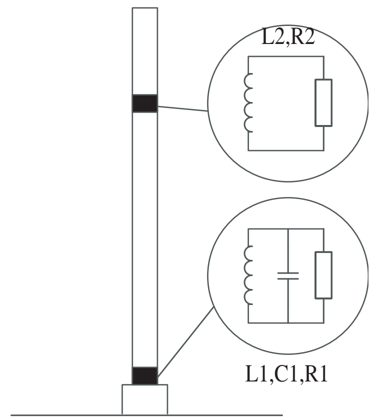


Figure 7. The load structure of antenna.

where $\omega_i (i = 1, 2, \ldots, N)$ is the N-th frequency point; $VSWR(\omega_i)$ and $G(\omega_i)$ refer to the VSWR and gain of the antenna at ω_i; G_0 is a rated gain; A_i is an adjusting parameter whose function is to weigh the broadband impedance characteristics and gain characteristics of the antenna; W_i is the weighted value of the VSWR at each frequency point, and its value depends on the relative importance to $VSWR(\omega_i)$. On the one hand, it retains a good VSWR, and on the other hand, it rejects bad VSWR. Obviously, the smaller the value of the objective function is, the better the optimization effect is.

A matching network is added at the bottom of the antenna, which combines transmission line transformer and lumped parameter matching network, and a network topology with "Γ" shape is composed of transformer cascade lumped parameter elements. As shown in Figure 8, the lumped parameter elements mainly choose low-consumption capacitance C and inductance L. The two branches of the "LC" matching network consist of a series LC and a parallel LC structure, respectively. The component parameters of each band will be determined by GOA optimization. The objective function should minimize the average VSWR in the frequency band, which can be given by the following formula.

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

In order to better meet the requirements of antenna VSWR and gain, the optimized component parameters are different in each band. That is to say, each band will correspond to a set of loading and matching network (transmission line transformer) structures, and real-time selection will be carried out through radio frequency switch control, as shown in Figure 6.

According to the design of the antenna structure and the optimization of the algorithm in Section 3, GOA is used to optimize the loading network and matching network of each band based on the principle of minimizing antenna load, and the optimization results are shown in Table 2 and Table 3.

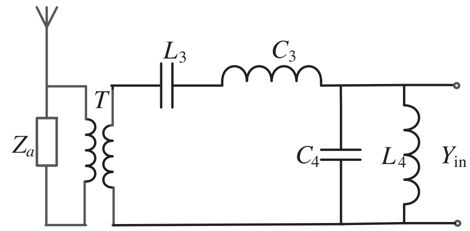


Figure 8. The matching network of antenna.

Table 2. Optimal values of loading element.

Frequency band	R_1 (Ω)	L_1 (μH)	R_2 (pF)	L_2 (μH)	C_2 (pF)
Band I	400	30	1000	4.2	1
Band II	400	30	-	-	-
Band III	400	30	-	-	-

Table 3. Optimal values of matching element.

Frequency band	T	L_3 (nH)	C_3 (pF)	L_4 (μH)	C_4 (pF)
Band I	2	0.93	283	2	260
Band II	-	620	185	1.5	78
Band III	2.5	270	116	0.5	0.2

4. ANTENNA MEASUREMENT AND ANALYSIS

In order to better verify the effectiveness of the proposed reconfigurable antenna and take into account the possibility of implementation, the scale model of the designed antenna is made in a ratio of 10 : 1, and the electrical parameters of the scale antenna are measured.

4.1. Scaling Model

According to the structure scheme of Section 3, Figures 6–8, a scaling model of 1-meter reconfigurable whip antenna is established. As shown in Figure 9, the frequency is set to 30 $\sim$ 300 MHz; the frequency interval is set to 5 MHz; the upper end of the antenna is a common loading point for three bands; and a mechanical switch is added in the middle of the antenna to control the radiator of band I and II to be turned on and the radiator of band III to be disconnected. In order to simplify the structure of the antenna, the second load network and the matching network of band I are merged into circuit "1". The labels "1", "2", and "3" in the figure represent the matching network of bands I, II, and III, respectively.

4.2. Measurement and Analysis

The VSWR, gain, and efficiency curves of a new type of HF broadband frequency reconfigurable antenna are shown in Figure 10, and the horizontal and vertical patterns are shown in Figure 11, respectively, compared with the traditional broadband whip antenna.

Within 3 $\sim$ 6 MHz band, the VSWR of reconfigurable antenna is less than 3 at 85% of frequency points, which is slightly larger than that of traditional broadband antenna, but the measured results are obviously better than the simulation ones, because 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 actual measured antenna can obtain better standing wave ratio

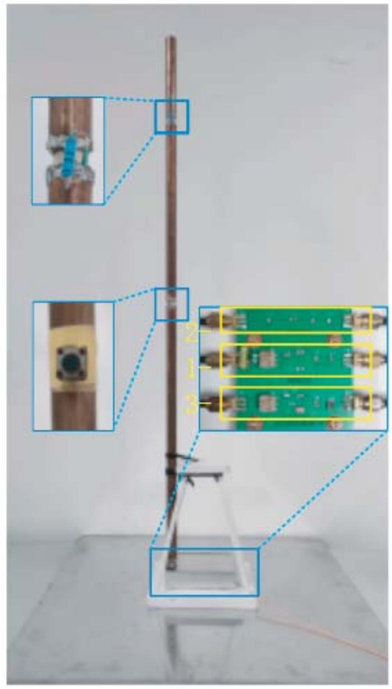


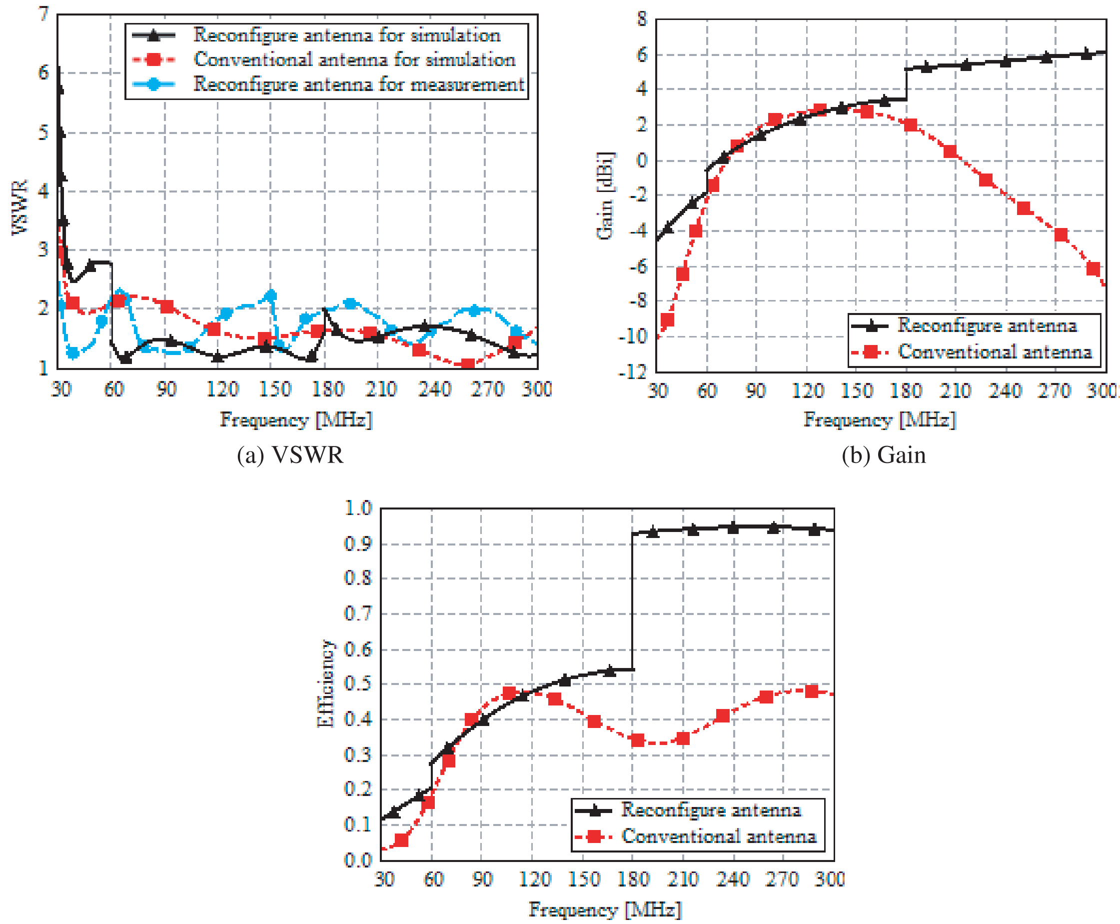
Figure 9. Test entity diagram of the proposed antenna.

performance in the low frequency band. The gain is greater than -4.5 dB, the maximum up to -1.8 dB, which is up to 6 dB higher than that of traditional broadband antenna; the efficiency is greater than 11.5%, up to 21%, the maximum up to 8% higher than that of traditional broadband antenna; the horizontal pattern is still circular, and the vertical pattern remains half of "∞" shape.

Within $6 \sim 18$ MHz band, the VSWR of reconfigurable antenna is less than 1.6, which is obviously lower than the traditional broadband antenna, but the actual measured results may fluctuate slightly under the influence of the environment. The gain is greater than -0.5 dB, and the maximum is 3.5 dB, which is slightly larger than that of traditional broadband antenna. The efficiency of reconfigurable antenna is greater than 28%, and the maximum is 54%, majority of which is higher than that of traditional broadband antenna. The horizontal pattern is still round, and the vertical pattern remains half of "∞" shape.

Within $18 \sim 30$ MHz band, the VSWR of reconfigurable antenna is below 2, which fluctuates slightly with traditional broadband antenna; the gain of reconfigurable antenna is greater than 5.2 dB, up to 6.1 dB, which is much higher than that of traditional broadband antenna; the efficiency is greater than 93%, which is much better than that of traditional broadband antenna; the horizontal pattern is still circular, and the vertical pattern remains half of "∞" shape without the phenomenon of warping in any direction.

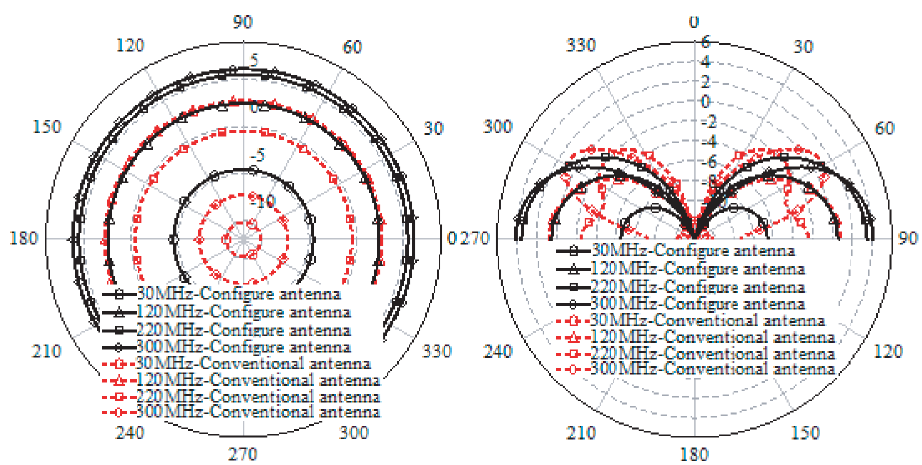
After frequency reconfiguration, band I ($3 \sim 6$ MHz) of 10 m HF broadband whip antenna greatly improves the gain and efficiency of antenna under the condition that the VSWR is basically satisfied. It is because the frequency band of the optimized antenna is narrowed, which can be better optimized according to the electrical characteristics of the antenna in the low frequency band, rather than sacrificing the radiation performance of band I in order to take care of the whole band as the traditional broadband antenna. Although band II ($6 \sim 18$ MHz) has also narrowed the optimized band range, the VSWR has been improved very well, but the gain has not been improved significantly. It is because, in principle, band II and band I share an upper loading point to minimize the antenna complexity. The upper loading point gradually increases the loss of antenna at band II, so band II is limited to complete band I. The performance of band III is improved, and the switching design in the middle of band III ($18 \sim 30$ MHz) skillfully reduces the height of antenna to 5 meters, so that the height of antenna is always kept below half wavelength, effectively avoiding the phenomenon of antenna pattern warping.



(a) VSWR (b) Gain

(c) Efficiency

Figure 10. The characteristic curve of configure antenna.



(a) Horizzontal pattern (b) Vertical patternn

Figure 11. Radiation patterns of configure antenna.

5. CONCLUSIONS

A novel frequency reconfigurable HF broadband whip antenna is designed in this paper aiming at the problems of low gain, low efficiency, and pattern warping in the high frequency band of the existing

10-meter HF broadband whip antenna. This paper proposes a band-by-band loading matching and reconfiguration technique, which mainly improves the gain in the low frequency band and the pattern in the high frequency band. Establishing antenna model in FEKO based on moment method calculation and optimizing 10-meter short-wave whip antenna in different bands by means of GOA can not only improve the gain and efficiency of antenna in low and high frequency bands, but also effectively avoid the problem of warping in antenna pattern. This provides a new design method for optimizing short-wave broadband antennas.

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