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A No-Network Matched High Gain Vertical Array Antenna for VHF Band Applications

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Abstract—This paper proposes a design method of vertically polarized VHF high-gain antenna, a four-element array form. Our design improves the overall gain of the antenna and reduces its loss. In our design, the conventional impedance conversion methods are abandoned. Instead, we directly use transmission lines for impedance match which greatly reduces the loss of the antenna in the frequency range of 150 MHz–300 MHz, ensuring that the antenna provides a higher gain, and its signal transmission efficiency is also improved.

1. INTRODUCTION

In the VHF communication process, the power loss of the transmission path [1] is:

$$L = 10n\log(d) + L_0\,\mathrm{dB} \tag{1}$$

$$L_0 = 20\log\left(\frac{4\pi}{\lambda}\right) \tag{2}$$

where L is the path loss in dB, and L_0 is the attenuation at 1 m in free space. d is the distance between the transmitter and receiver antennas in meters, and λ is the wavelength in meters. The value of n intrinsically embeds the effects of all propagation mechanisms including attenuation, diffraction, reflection, etc. Setting the value of n in the frequency range of 150 MHz–300 MHz into Eq. (1), the path loss is over 89 dB high in a distance of 1000 meters. To achieve a reasonable communicate distance and acceptable signal quality, amplifiers are often installed on the antennas to obtain a stronger signal. However, the noise is also amplified, which will reduce the value of the signal to noise ratio (SNR) in the system. In the receiving system, the antenna's SNR is [2] defined by formula (3):

$$\mathrm{SNR} = \frac{\tau\eta_r\lambda^2 D}{4\pi K T_0 B\left(1+\tau+\tau\eta_r\left(\frac{T_a}{T_0}-1\right)\right)} \tag{3}$$

where λ is wavelength, D the directivity coefficient, τ the mismatch loss, T_0 the reference temperature (K) taken as 290 K, k the Boltzmann's constant $= 1.38\times10^{-23}$ J/K, T_a the noise temperature of the antenna, η_r its radiation efficiency, and B the noise power bandwidth of the receiving system (Hz). It can be seen from Eq. (3) that the gain will be of great advantage on the SNR. With the synthetically analysis of Eqs. (1), (2), and (3), it is clear that the path loss was fixed. Raising the SNR will be an appropriate way to improve the communication performance. The antenna gain is a critical factor of the SNR. In shipborne and vehicular communications, high gain VHF antenna provides higher performance.

Recent advances in VHF antennas have attracted great interest in their broadband performance, efficiency, and multi-polarization behaviour. To broaden the VHF antenna bandwidth, on-body

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network [3] with the genetic algorithm or ferrite-loaded network [4] is applied. However, since the efficiency is decreased by these network units, the achieved gain of these antennas is not higher than 0 dBi. Furthermore, both of the dual-linear polarized [5] VHF antenna and horizontally polarized loop antenna [6] have a miniaturized size, but their gains are lower than 1.5 dBi. This results in a limited communication range. No-foster impedance matching technique is introduced in [7, 8], where the performances of the antennas can be improved; however, the gain of the antennas remains low as a result of the attenuation by their complicated network. By employing the printed circuit board (PCB) [9] and optimization of on-body integrated loads, the gain can be further improved up to 5 dBi for specific frequencies. In [10], the transmission line matching method is used to increase the horizontal gain of the VHF antenna to 6.8 dBi in the frequency of 50 MHz to 500 MHz. The vertical polarized gain is however not mentioned.

In this paper, a novel VHF antenna design on transmission line matching method is proposed. Compared with most of the ordinary VHF antennas, the gain of our proposed antenna is much higher over the whole bandwidth without any active amplifier circuit. The gain was 8 dBi at the frequency start point and rose with the increasing frequency. Our proposal has a concise structure that was constituted of 4 vertical dipole arrays and a smooth mantle. The primary difference of our proposal and the conventional design is the matching method. Being abandoned the network which consisted of the components that can cause power loss such as inductance, capacitor, and resistor, the VHF antenna proposed in this paper used a low-loss transmission line to achieve an impedance match. Detailed design concept and measurement results are presented in the following section. All numerical models and simulations in this letter were performed using EMSS's FEKO.

2. ANTENNA CONFIGURATION

Two important issues should be considered in antenna design including application scenarios and performance requirements. For instance, to be installed on the shipboard, the VHF antennas need to be antivibration and wind-resistant. Since the available space for installation is limited, the antenna size is also an important factor. Therefore, whip antenna is one of the most commonly used antennas. A common vertical whip antenna is usually produced in either dipole or monopole form, and in either case, the antenna gain is less than 3 dBi. The performance of a monopole whip antenna is also easily affected by the size and type of material of the mounting surface. Here we focus on vertical dipole whip antenna. Our objective is to increase the VHF antenna gain while keeping the shape of the antenna; therefore, linear array structure is considered in our design.

2.1. Array Cell Design and Impedance Factor

Here we use FEKO to simulate the impedance of the antenna. The simulation model is shown in Fig. 1. To obtain the optimal length of the cell vibrator, we use the mean value in the vicinity of the stepping algorithm to optimize resonator of 0.5λ and use 100 points in our simulations. By setting the optimum resonator length of 0.464λ, the antenna element vibrator length is 0.48 m [11]. The impedance characteristics are shown in Fig. 2. In actual cases, the antenna requires a certain bandwidth to meet its different communications applications, and here we consider a broadband antenna design [5].

Common methods for increasing the antenna bandwidth are 1) matching network method and 2) changing the form of the vibrator. The former method uses the network to change the impedance of the antenna, thus broaden its bandwidth. Doing this, however, introduces an additional loss thus further decreases the antenna efficiency. Therefore, to improve the antenna bandwidth, it is often better to change the form of the antenna. Given the same conditions, the thicker the antenna vibration is, the better its wideband impedance performance is. Considering the technical specifications and anti-vibration characteristics, a cylindrical vibrator with a diameter of 114 mm is used in our design. The antenna bandwidth, in this case, is 150 MHz, and the operational frequency is 150–300 MHz. The simulated impedance results are shown in Fig. 2.

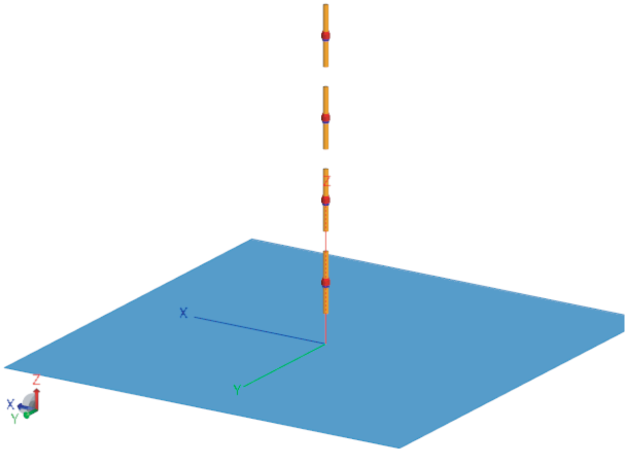


Figure 1. The simulation model.

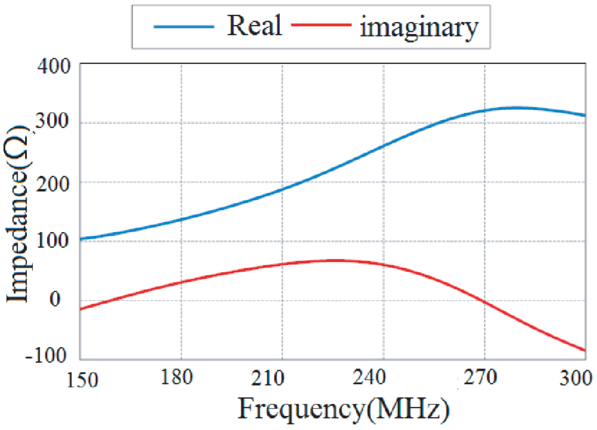


Figure 2. Impedance versus frequency.

2.2. Array Design and Pattern Simulation

To effectively improve the antenna gain, while maintaining an acceptable antenna size, a 4-group dipole array is used. As also used in [12] the array elements are centre spaced on half wavelength.

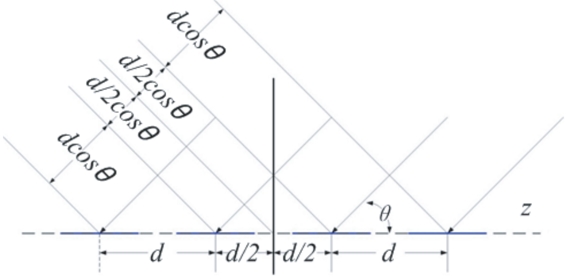
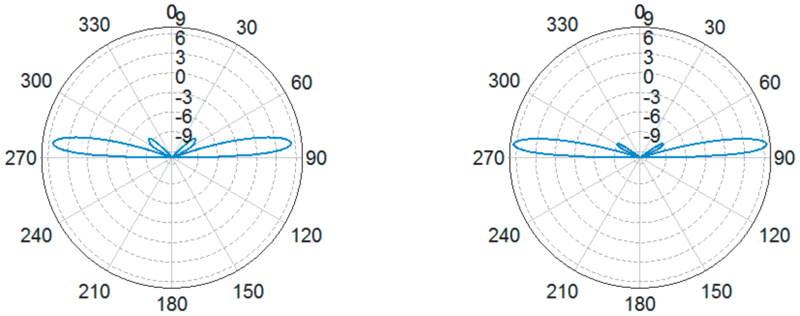


Figure 3. The array model.

The array factor is: $AF{=}I_0e^{j\xi_0}+I_1e^{j\xi_1}+I_2e^{j\xi_2}+\ldots$. The phase centre of the dipole is at its feeding point as shown in Fig. 3. The synthesized gain is then obtained as follows. We take the intermediate phase array element as 0 and set $I_0 = I_1 = I_2$. The array factor is:

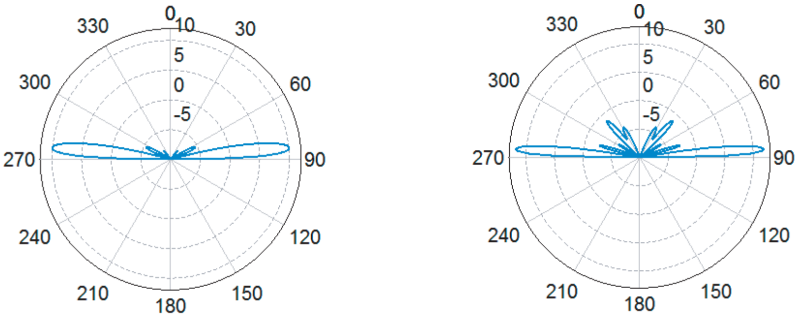
$$AF = Ie^{-j\beta(3d/2)\cos\theta} + Ie^{-j\beta(d/2)\cos\theta} + Ie^{j\beta(d/2)\cos\theta} + Ie^{j\beta(3d/2)\cos\theta}$$

The center spacing of the phase array is $\lambda/2$, therefore, $\beta d/2 = \pi/2$, $3\beta d/2 = 3\pi/2$, $AF = I(2\cos(3\pi/2\cos\theta) + 2\cos(\pi/2\cos\theta))$. The maximum value is obtained for $\theta = \pi/2$. Based on the analysis above, we set the coefficient of the array as follows: the distance between the adjacent dipoles was 1.22 m, a space that was optimized to adapt the broadband requirement. The phases fed on each point were 0 degrees. This made the maximum synthetic beam emerge on the right head of the antenna. The pattern of the array antenna was simulated by the FEKO, as the shape of the horizontal plane pattern was disk-shaped and kept unchanged in all the frequencies, and we only consider the vertical plane pattern here. The simulated vertical plane patterns for different frequencies are presented in Fig. 4. From the four charts displayed in Fig. 4, we can find the array antenna has a higher gain over 8 dBi, and the 3 dB beamwidth was nearly 10 degrees. The higher gain guaranteed better communication performance, and the narrow beamwidth is propitious to anti-noise interference.



Gain [dBi] (Frequency = 150 MHz; Phi = 0 deg)

Gain [dBi] (Frequency = 180 MHz; Phi = 0 deg)



Gain [dBi] (Frequency = 200 MHz; Phi = 0 deg)

Gain [dBi] (Frequency = 300 MHz; Phi = 0 deg)

Figure 4. The vertical radiation patterns for different frequencies.

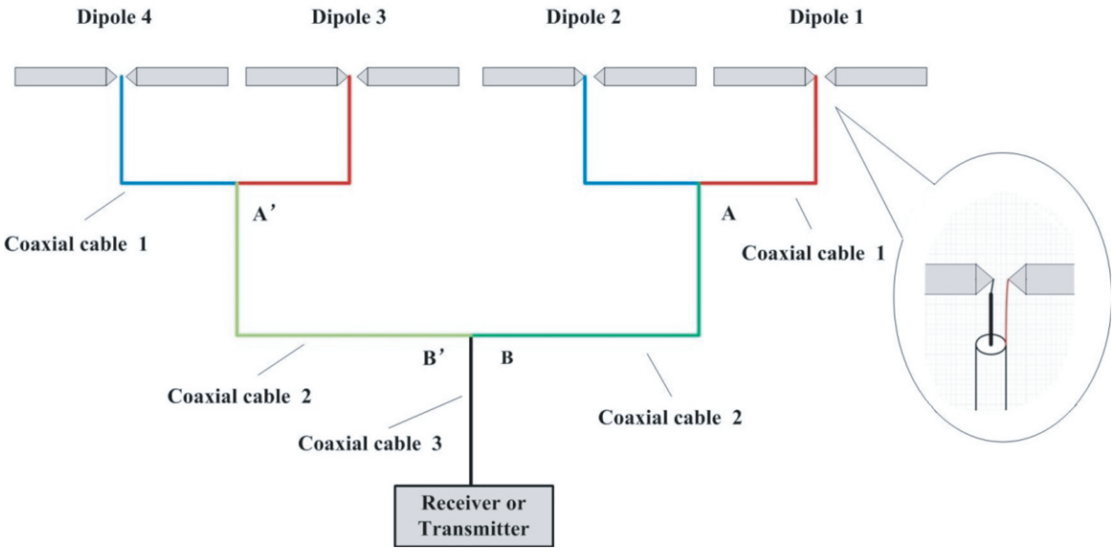


Figure 5. Transmission line impedance match.

2.3. Design of Impedance Match Transmission Line

As shown in Fig. 1, the impedance of the dipole cell is about 100 Ω. To obtain an output impedance of 50 Ω, the method of transmission line impedance match is adopted as follows. As shown in Fig. 5, we connect the two dipoles in parallel by two 50 Ω coaxial cables. Two 50 Ω output impedances are then obtained at points A and A'. Secondly, we connect two 75 Ω coaxial cables in series to points A and A'. Here the output impedances at points B and B' are then equal to 125 Ω. We then connect B and B' in parallel. The theoretical input impedance is therefore 62.5 Ω. Finally, a 50 Ω coaxial cable is connected to this point, and then the final output impedance is equal to 50 Ω. The impedance can be optimized by adjusting the length of the cable connecting A and B.

In Fig. 5, line # 1 and line # 3 are 50 Ω coaxial cables; line # 2 is 75 Ω coaxial cable, and its length is $\lambda/2$. Low-loss ultra-soft cables were used to assemble the transmission line. The diameters of 50 Ω cables were 9 mm and 7 mm for 75 Ω coaxial cables. Furthermore, each dipole element has a length of 0.9 m; the element spacing in the array is $\lambda/2$; the vibrator diameter is 90 mm; and the total antenna height is 5 m. As it is seen, this method does not use the matching network, thus losses are effectively reduced. This further improves the antenna efficiency while increases its gain.

3. MEASUREMENT RESULTS

The fabricated high gain VHF antenna of our design is shown in Fig. 9, and details of the connection point of the dipole are shown in Fig. 10. We then performed measurements to test its radiation performance and impedance match.

3.1. VSWR

The simulated and measured VSWRs are shown in Fig. 6. The VSWRs are less than 1.9 throughout the bandwidth. It shows that the antenna provides a good impedance match.

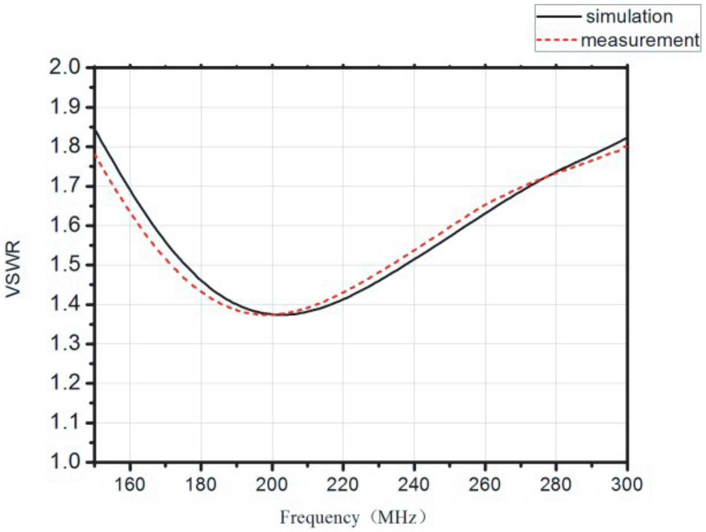


Figure 6. The simulated and measured VSWRs.

3.2. Realized Gain

The realized gain measurement [11] is shown in Fig. 7. The gain comparison measurements are used in our test. The reference antenna is a standard dipole at the considered frequency range. The realized gain is then calculated by:

$$G_T = G_s + 10\log\left(\frac{p_T}{p_s}\right) \tag{4}$$

where G_T and G_S are in dB and denote the gain of test and standard antennas. In Fig. 8 we plot the simulated and measured realized gains along the maximum direction. It is seen that the realized gain throughout the bandwidth is greater than 8.3 dB, and the maximum gain is 11.9 dB which is at 300 MHz.

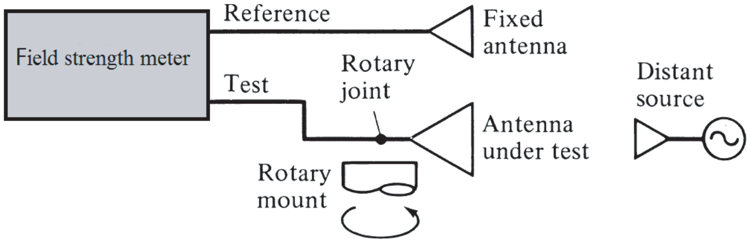


Figure 7. Realized gain measurement.

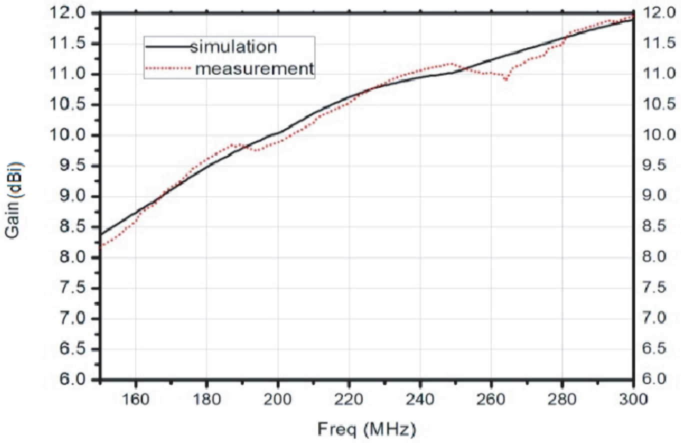


Figure 8. The simulated and measured gain plots.

Figure 9. The fabricated high gain VHF antenna.

Table 1. Comparison of the VHF antennas in this area.

Antenna Name	Our Design	ferrite-loaded VHF antenna	Dual-linear polarized VHF antenna	On-body integrated loads VHF antenna
Gain (dBi)	8–12 dBi	Lower than 0 dBi	1.5 dBi	Lower than 5 dBi
VSWR	≤ 2.0	≤ 2.5	≤ 2.0	≤ 2.5

The radiation performance of this antenna is also much better than most of the existing VHF antennas. A comprison of the performance of our design and the other antennas in this area is shown in Table 1.

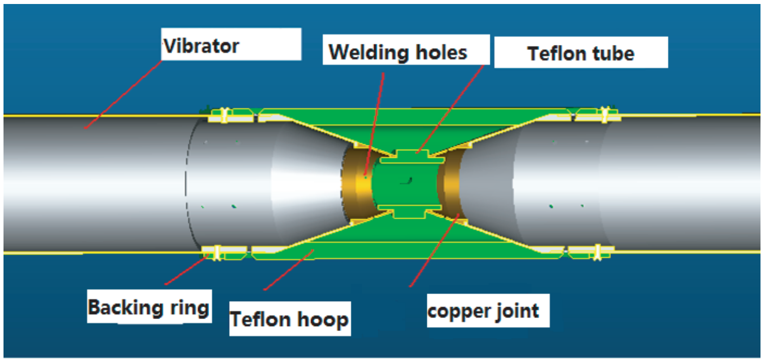


Figure 10. The form of antenna connection.

4. CONCLUSION

This paper presented the design and implementation of a novel high gain vertically polarized VHF antenna. We used the transmission line impedance match in our design and showed that this improved the antenna efficiency. The realized VSWR and gain were also measured and compared with the simulations. These results demonstrated a promising achieved performance of the proposed design. Our subsequent studies will be focused on further improvement of the antenna bandwidth.

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