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Article

# A Design of Wideband Loaded Sleeve Monopole Embedded with Filtering High-Low Impedance Structure

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**Abstract:** In this paper, A wideband and filtering monopole is presented for applying in remote terrestrial omnidirectional communication systems. The antenna consists of a sleeve monopole loaded by lumped parallel RLC circuit and an embedded high-low impedance structure in the sleeve section. The high-low impedance structure makes the antenna acquire filtering character in a compact structure. The sleeve structure and the lumped parallel RLC loads make the antenna a wideband radiation character in omni-direction. For verification, a prototype of the designed antenna, operating in 200-1500 MHz, is designed, fabricated and measured. The experiment results show that the antenna covers the design band with a  $VSWR < 2.5$ , a measured gain  $> 0$  dB and a satisfactory filtering character from 1700 to 4000 MHz.

**Keywords:** wideband monopole; load antenna; filtering antenna

## 1. Introduction

The development demand of high communication quality for terrestrial wireless omnidirectional communication puts forward the requirements of wideband, integration and anti-interference for antennas in the communication system [1–4]. The realization of a wideband monopole covering multiple bands of different systems could reduce complexity of multiple communication platform. On the other hand, a well-designed monopole with a large frequency ratio is a trend to meet the future needs of increasing communication capacity [5–7]. Besides, with the development of wireless communication, the demand of integrating RF front-end devices has become a trend in the design of modern wireless communication system. However, traditional monopole only works as an electromagnetic energy conversion device between closed wave guide space and open free space. To provide multifunctional ability for monopole, it is a good idea to combine antenna with filtering function, since antenna integrating with filtering function is popular in other antenna design, such patch antenna [8–10]. Integrating a filtering function in antenna not only can enhance electromagnetic immunity of communication system, but also can reduce the total size and weight of antenna [11–13].

Ordinary monopole with its simple linear structure is usually regarded as an open-end transmission line and shows the classic resonance character. A normal quarter-wavelength monopole only shows about ten percent relative bandwidth for  $VSWR < 2$  near resonant frequency [14,15], which is only suitable for the narrow band application. To meet the requirements of wideband application in terrestrial wireless omnidirectional wideband communication, it is eager to resolve the inherent resonant character in ordinary monopole. In wideband antenna design, the radiation bandwidth and impedance bandwidth of antenna have to be considered at the same time so as to realize a workable wideband front-end device for wideband communication system. For broadening the radiation bandwidth of monopole, loading ordinary monopole with lumped element is an effective way to alter current distribution on monopole and realizes the wideband radiation character while keeping

the linear shape of monopole. With difference loading strategy [16–19], bandwidth could be broadened to thousand percent of relative bandwidth. As for broadening the impedance bandwidth of monopole, some appendix radiation structure such as hat or sleeve structure could be a good candidate, especially for electrical small monopole design. Numbers of novel variant of hat or sleeve structure play an important role in wideband antenna design [20–25].

Traditional monopole designs mainly focus on improving radiation character such as broadening radiation bandwidth or increasing radiation efficiency [26]. However, the traditional monopole does not have filtering function. As the core functional module of wireless communication system, filtering technology plays a key role in suppressing interference and purifying spectrum in the electromagnetic signal transceiver link. Its technology evolution has always been an important driving force to improve the performance of communication systems. In the traditional communication architecture, the filter and the antenna are designed independently. The filter, as a separate functional unit, needs to be optimized separately. And the antenna is only working for the radiation and reception of space electromagnetic signals. The electrical connection between antenna filter depends on the transmission line. This architecture leads to a double loss in the signal receiving path. The concatenation of lossy transmission lines and filters not only increases the size, weight and cost of the system, but also causes significant signal energy attenuation, especially in low signal-to-noise ratio scenarios, which seriously affects the receiving sensitivity.

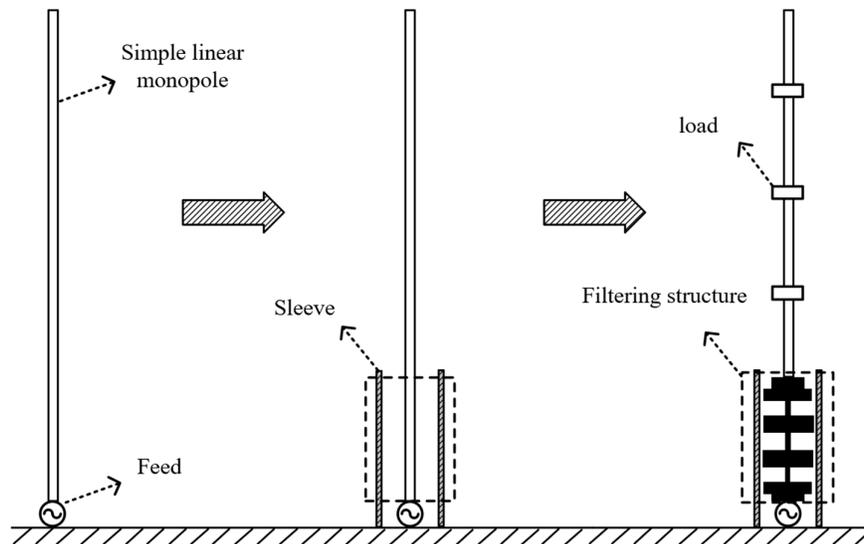
To adapt with the demand of the integration development of RF front-end devices, integrating filtering character in monopole is a promising design. The design of filtering monopole could refer to other filtering antenna design. With the help of the mature filter synthesizing method, a simple way to realize filtering antenna is just introduce filtering structure at the port of the designed antenna to realize controllable passband and stopband [27–29]. By this method, although antenna could possess a filtering function straightforward, the filtering structure and the radiation structure still remain relatively independent. Consequently, the filtering character and the radiation character of the filtering antenna are still designed relatively separately and also, the total size is not compact enough. For consideration of size reduction and function integration, other way such as the fusion design method of filtering antenna could make use of antenna structure for realizing filtering function more effectively. In the fusion design method, filtering antenna design employs the eigenmode analysis of the designed antenna and then adjusts the structure of the radiator to realize filtering character [30–32]. The adjustment of the structure of the design antenna is easily implemented in patch antenna or antenna with cavity structure, since there are at least two dimension to adjust mode distribution on radiator. But for filtering monopole design, with the constrain of keeping the linear shape of monopole, it is hard to realize filtering character by the eigenmode analysis method due to no adequate place to adjust mode distribution on linear shape structure, especially for whip monopole that making use of wire as the radiator.

To achieve filtering character and compact size while obtaining wideband character in monopole design, this paper presents a wide band monopole integrating compactly with filtering function by a structure-reused technique that hybridizing the sleeve structure and the high-low impedance structure to realize filtering character for antenna. Section 2 addresses the design of the presented monopole. Starting from the familiarly simple linear monopole, the sleeve structure, the high-low impedance structure and the distributed lumped loads are employed gradually with little size expansion. Simulation shows that the presented monopole obtains wideband and filtering character in compact design. In section 3, the designed monopole is carried out with a fabricated prototype for verification. Tested result shows close the port character and radiation character between experiment and simulation. For comparison, Section 4 discusses the realized character of the design monopole against other similar designs of wideband monopole. The presented monopole realizes wideband character while obtains filtering superiorly in monopole design. Section 5 concludes this work gives a promising sight on the presented monopole.

## 2. Antenna Design and Configuration

### 2.1. Antenna Configuration

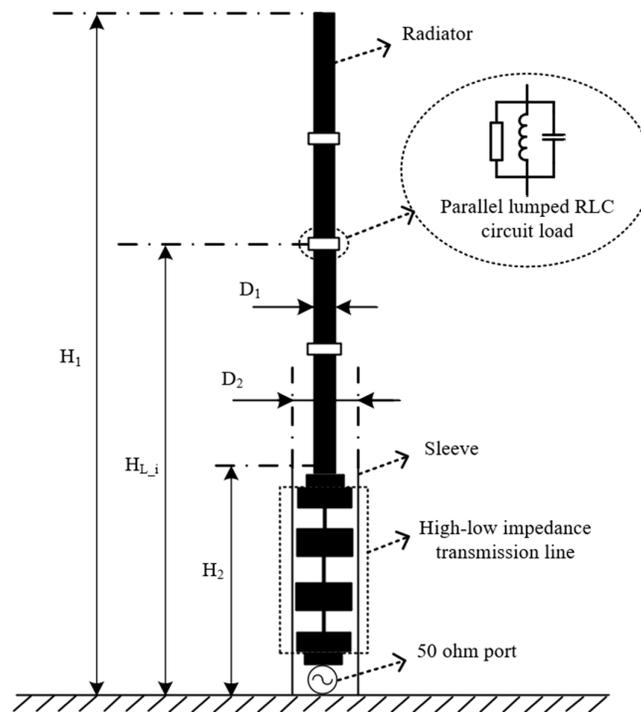
The overall design scheme of the presented monopole is depicted in Figure 1. The initial structure is a familiarly simple whip monopole with narrow band character. By introducing a sleeve structure, the monopole's bandwidth can be broadened to some extent with no obvious size expansion. So, the lower radiator of the initial monopole is converted into the inner conductor of the sleeve structure. The outer conductor of the sleeve plays a role as a part of the radiator of the sleeve monopole. The lower part of the initial monopole and the inner side of the sleeve composes a transmission line in the sleeve monopole now. And then, for obtaining a filtering function for the monopole, the lower part of the initial monopole in the sleeve structure is replaced with a multistage metal structure. This multistage structure accompanying with the inner conductor composes a high-low impedance transmission line with a required filtering function. Since the filtering function is obtained by just the replacement of the inner conductor of the sleeve structure, no any size expansion take place in the introduction of filtering function for the monopole. The presented monopole is design with filtering function in compact size. After the filtering structure is designed, the upper part of the monopole in current design is still a normal whip radiator. For broadening the bandwidth of monopole further, the distributed lumped elements are loaded on the radiator. Acceptable filtering character and radiation character can be obtained by optimizing the size of the embedded high-low impedance transmission line in the sleeve and the value and the position of the loaded element at the same time.



**Figure 1.** The design scheme of the presented wideband filtering monopole.

The detail structure of the presented wideband filtering monopole is shown in Figure 2. The monopole is fed on ground by common 50 ohm coaxial port as the normal feed network of ordinary monopole. For applying in mobile vehicles or air craft communication, the working band is design from 200 MHz to 1500 MHz. To have lower VSWR character around 200 MHz, the total length  $H_1$  of the presented monopole as Figure 2 shown is selected as 30 cm. The sleeve made of a hollow cylinder with its diameter  $D_2=5$  cm is design encloses the lower part of the radiator with length  $H_1=10$  cm. And the bottom of the sleeve is connected to ground. For rejecting common frequency band of 2450 MHz and some 5G communication bands in 3000-4000 MHz, the design monopole requires a lowpass filtering character above the design working band. In the hollow of the sleeve, a multistage structure

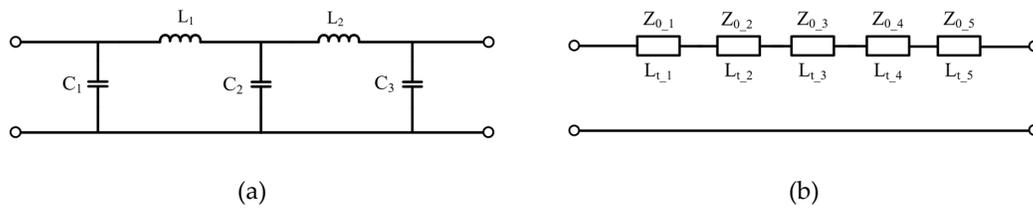
is designed and works as a high-low impedance transmission line with a low pass filtering character. The detail of high-low impedance transmission line is discussed in section 2.2. The upper radiator more like traditional monopole and also made of a hollow tube with diameter  $D_1=1.5$  cm. But for broadening the band width of the presented monopole further, three lumped circuits are loaded on the radiator of the presented monopole. All lumped circuits are made of parallel RLC element to adjust the current distribution on the radiator resulting in wide band omni-direction radiation character. The detail of these distributed lumped loads is addressed in section 2.3.



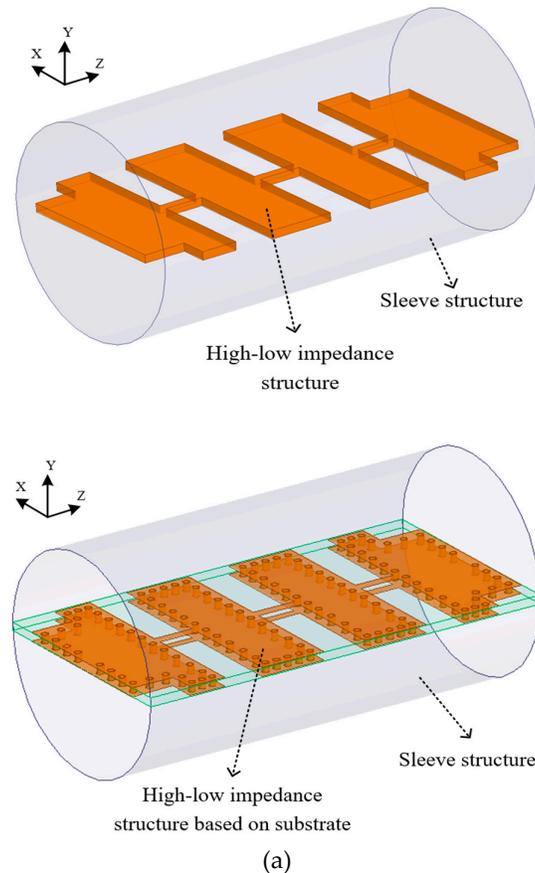
**Figure 2.** The detail configuration of the presented wideband filtering monopole.

## 2.2. Design of Filtering Structure

The High-low impedance transmission line design start from a five order Chebyshev lowpass circuit as Figure 3 (a) illustrated to obtain a rejection character below -20 dB from 1700 MHz to 4000 MHz. By applying Richards's transformation and Kuroda's identities [33], the lowpass circuit in Figure 3 (a) can be converted to another circuit in a form of altered impedance transmission line as Figure 3 (b) shown. To realized the lowpass circuit of Figure 3 (b) in the sleeve structure in Figure 2, the high-low impedance transmission line is designed in the sleeve as illustrated in Figure 5 (a). The inner surface of the sleeve works as the outer conductor of the high-low impedance transmission line. Since this filtering structure is placed at the lower part of the monopole as Figure 2 shown, the high-low impedance structure is also working as a supporter for the upper part of the monopole. Although the high-low impedance structure is made of metal, the high impedance transmission line is too thin to support the upper part of the monopole. Even though some Teflon supporters could be introduced to maintain the stability of the structure, extra design of this Teflon supporter would lead to a complex design of this filtering structure. Taking into account the support problem, the high-low impedance transmission is designed by two side patch structure as Figure 5 (b) shown. The dielectric substrate works as the supporter for the high-low impedance structure and the upper part of the monopole at the same time.



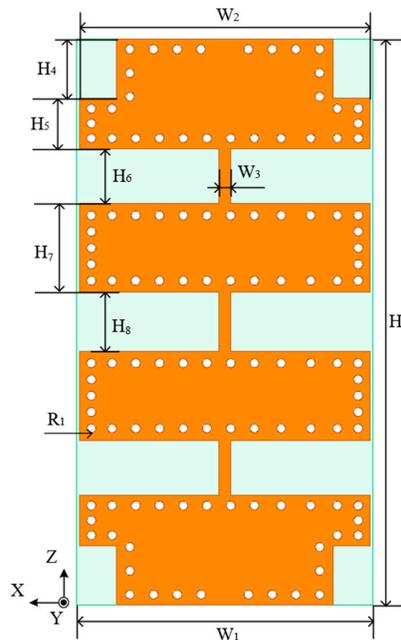
**Figure 3.** Lowpass circuit. (a) Five orders RC ladder Chebyshev lowpass circuit; (b) The converted high-low impedance lowpass circuit.



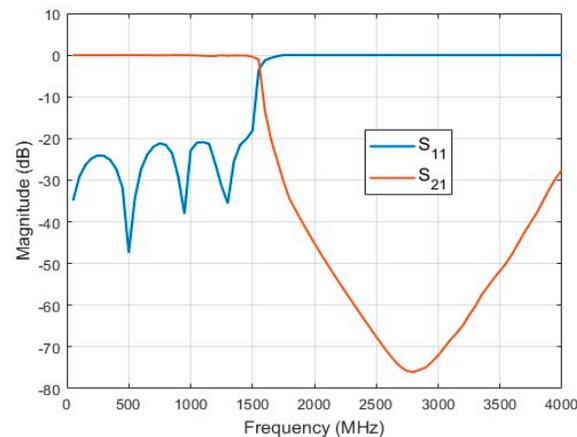
**Figure 5.** Filtering structure. (a) High-low impedance transmission line; (b) High-low impedance transmission line based on substrate.

The detail architecture of the top view the high-low impedance transmission line based on substrate embedded in the sleeve is illustrated in Figure 6. Two copper patches etched on a substrate which is made of Teflon with relative permittivity of 2.1 work as the inner conductor of the high-low impedance transmission line. These two copper patches are connected to each other by numbers of via holes with radius of 1.5 mm to analog the filtering structure in Figure 5 (a). The width of substrate  $W_1$  is 48 mm which is the same as the inner radius of the sleeve. But the width of the etched low impedance section of the high-low impedance transmission line  $W_2$  is 47 mm which is slightly shorter than  $W_1$ . So, the substrate can also work as supporter for inner conductor resided in transmission line. The other sizes depicted in Figure 6 deduced by Richards' transformation [33] are calculated from the lowpass filtering circuit in Figure 3 (b). The length of each low impedance section is optimized for compensating for the parasitic capacitance effect. As Figure 7 shown the optimized high-low impedance transmission line based on substrate achieves the desired low pass character with cut-off frequency resided around 1500 MHz and a stop band with  $S_{21}$  below -20dB from 1700

MHz up to 4000 MHz. Due to the fact that the low impedance line is tending to resonance around 4000 MHz, the rejection property from 3000 MHz to 4000 MHz become worse. However, the rejection property is still below -20 dB in these band and meets the rejection specification.



**Figure 6.** Top view of the high-low impedance structure based on dielectric substrate ( $W_1=48$  mm,  $W_2=47$  mm,  $H_3=95.4$  mm,  $H_4=10$  mm,  $H_5=8.5$  mm,  $H_6=9.2$  mm,  $H_7=15$  mm,  $H_8=10$  mm,  $R_1=1.5$  mm).



**Figure 7.** The filtering character of the high-low impedance structure.

### 2.3. Wide Band Filtering Monopole

After the filtering structure designed, the high -low impedance structure based on substrate is arranged in the sleeve as Figure 2 depicted. For obtaining satisfied radiation property, three lumped loads are arranged on the designed monopole as Figure 2 depicted. Each load is a parallel RLC circuit. The designed monopole is simulated by MoM to analog the electrical character. The positions of each load and the value of each load element is optimized for satisfactory electrical character. The optimized parameters of the loads are listed in Table 1. The positions of the loads are measured from ground. All the optimized values of each element are easy access in practical implementation.

The optimized gain in omni direction is all greater than 0 dB in the concerned band as shown in Figure 8. For comparison, the gain of ordinary monopole and the gain of ordinary sleeve monopole in omni direction are also plotted in Figure 8. These two monopoles have narrower bandwidth due to the occurrence of gain zero in omni direction. But the presented monopole has not experienced such gain zero in omni direction since the loads of the presented monopole has been properly designed. Figures 9 and 10 illustrate the E-plane patterns and the H-plane patterns of the designed monopole at some typical frequencies in the concerned band. The optimized monopole has relatively uniform radiation character in omni direction in the concerned band. The radiation efficiency of the design monopole is above 40% across the working band as shown in Figure 11. For wideband application, the radiation efficiency is acceptable. As Figure 12 shown, the optimized monopole obtains VSWR below 3, which is an acceptable port property for wideband application.

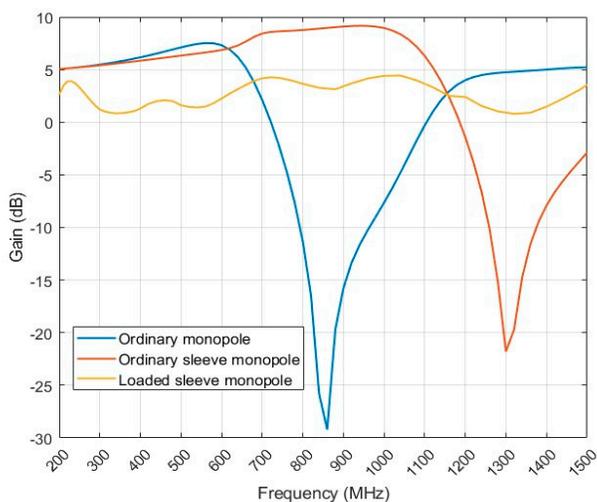


Figure 8. Gain of the designed monopole in passband.

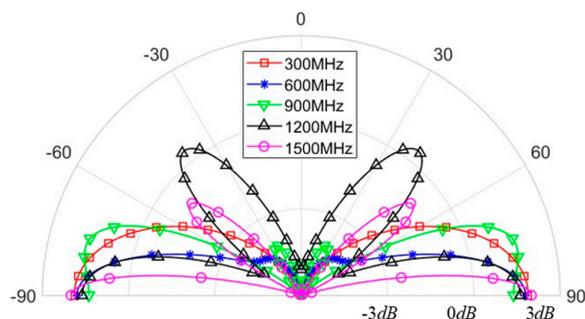


Figure 9. E-plane patterns of the designed monopole.

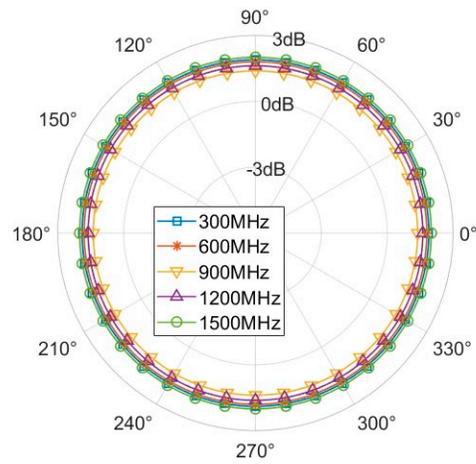


Figure 10. H-plane patterns of the designed monopole.

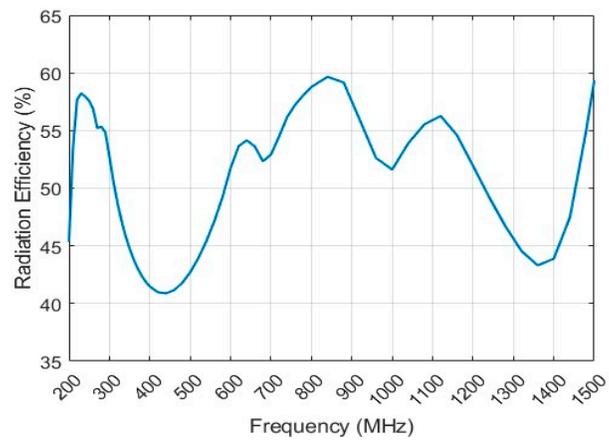


Figure 11. Radiation efficiency of the designed monopole.

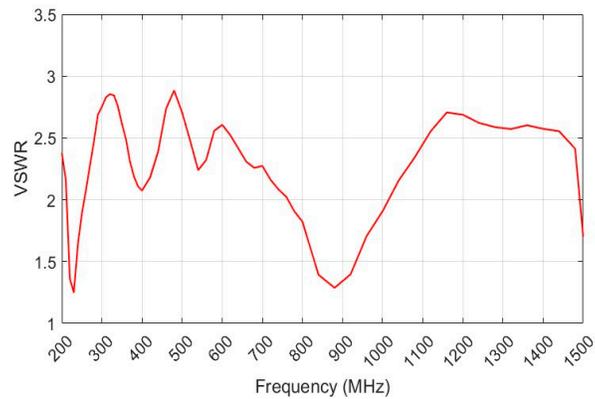


Figure 12. VSWR of the designed monopole.

**Table 1.** Parameter of optimized load of the lower monopole.

Load Position (mm)	Resistance (ohm)	Inductance (nH)	Capacitance (pF)
178	100	25	3
225	1600	8.5	1
265	200	10	1.2

### 3. Experiment and Result Analysis

A fabricated prototype is shown in Figure 13 in which the sleeve is separated apart for illustration. The designed monopole is fed by a common 50 ohm N-connector. The experiment is carried out in outdoor open half-space environment, as shown in Figure 14. The transmitting antenna and the receiving antenna are separated 20 m away for measurement of the far field at 200 MHz by employing the criterion of  $10\lambda$  for far-field judgment. The measured VSWR and the simulated VSWR of the presented monopole are shown in Figure 15. It can be seen that the presented monopole could cover a wide band of 200–1500 MHz with a VSWR < 3. Acceptable agreement between the simulation and measurement can be found. The differences between the simulation and measurement may come from the fact that the practical load circuits are fabricated with a little space in contrast to the point load in the simulation. The measured gain and filtering character of the presented monopole is shown in Figure 16. There is satisfactory agreement between the measurement and simulation. Figure 16 also shows the gains of an ordinary monopole and an ordinary sleeve with the same size. The presented not only has advantage in bandwidth but also in advantage in filtering character with stopband below -20 dB from 1700 MHz up to 4000 MHz.

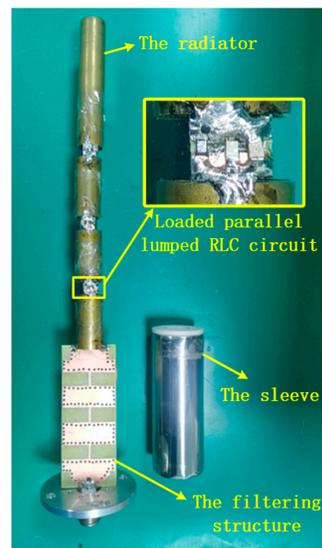
**Figure 13.** Fabricated prototypes of the designed monopole.



Figure 14. Experiment in outdoor open half-space environment.

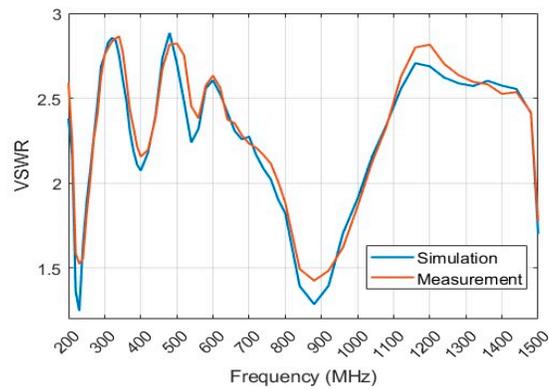


Figure 15. The measured and simulated VSWRs.

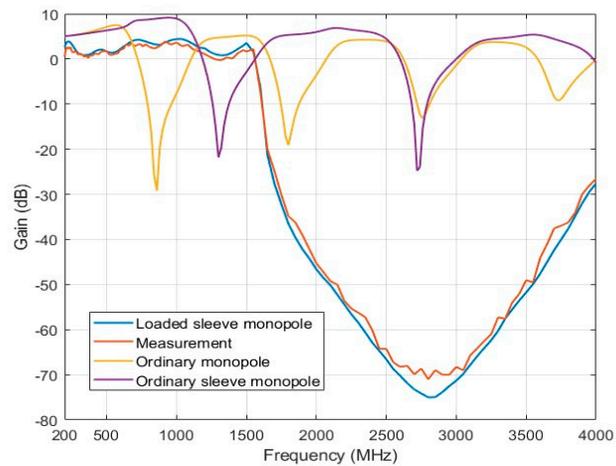


Figure 16. The measured and simulated VSWRs.

## 4. Discussion

Table 2 shows the performance comparison between the presented monopole and other reference monopoles. Ref. [34] and [4] presented some design with wideband character, but their gains are lower. Besides, there are no filtering character in that designs. In Ref. [29] and [35], the presented monopoles are all designed with filtering character and higher gain, but they can only be used for narrow band application. In sum, wideband and filtering character are achieved in this paper, the structure is simple and compact in size.

**Table 2.** Comparison of presented work with other works.

Ref.	Bandwidth (MHz)	Gain (dB)	Filtering character
[34]	100-550	-4	No
[29]	5835-6100	5.5	Yes
[4]	900-5200	0.8	No
[35]	2500-3500	2.5	Yes
This work	200-1500	0	Yes

## 5. Conclusions

A loaded sleeve monopole with wideband and filtering character is presented. By designing a high-low impedance structure in placement of the inner conductor of the sleeve, filtering character is achieved. Since no extra structure is introduced, the design realizes structure reuse and results in compact size. Lumped load technique is also employed to adjust the current distribution on radiator for broadening the bandwidth. The presented monopole was tested from 200 MHz to 4000 MHz with stable gain above 0 dB in passband from 200 MHz up to 1500 MHz and a satisfactory stopband below -20 dB from 1700 MHz up to 4000 MHz. With the merits of wide bandwidth, filtering, omnidirectional character and compact size, the presented monopole is a good candidate for vehicle terrestrial wireless omnidirectional communication.

**Author Contributions:** All authors have significantly contributed to the research presented in this manuscript; J.M. presented the main idea and wrote the manuscript; W.C. and X.Y. reviewed and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** Data are available based upon reasonable request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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