Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2013, Article ID 531419, 7 pages
http://dx.doi.org/10.1155/2013/531419

Research Article

Non-Foster Impedance Wideband Matching Technique for Electrically Small Active Antenna

Wenxing Li, Ning Zhai, Ruilong Chen, and Wenhua Yu

College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, China

Correspondence should be addressed to Wenhua Yu; wenyu@2comu.com

Received 28 July 2013; Accepted 12 September 2013

Academic Editor: Dau-Chyrh Chang

This paper investigates a non-Foster wideband circuit matching technique for an electrically small antenna (ESA). By introducing a negative impedance convertor into an active network, the active network can obtain an equivalent input gain at input port to improve gain, sensitivity and output ratio of signal to noise. In addition, it also increases the effective height of active antenna. The experimental results have verified the proposed method by using a 100 KHz–30 MHz wideband active receiving monopole antenna.

1. Introduction

With miniaturization of radio equipment, the broadband and compact antenna becomes more demanded for broadband communication equipment. As a well-known fact, an electrically small antenna usually presents a high radiation quality factor Q, and its impedance is characterized by a large reactance and a small radiation resistance. The gain bandwidth and efficiency of an electrically small antenna with a passive matching network are limited. Traditional active receiving antenna is composed of a field effect transistor (FET) with a high input impedance to achieve a wideband property [1]. However, due to suffering from the FET input capacitance an active network cannot achieve desired effective height.

The electrically small receiving antenna with Non-Foster matching can tickle the gain-bandwidth limitation, which was proposed by Harris, Myers, and Perry [2, 3]. This topic has drawn more attention for many years [4–12], and the significant achievements has made on this topic [8]. Though the existing techniques of electrically small antenna with non-Foster matching [9] network can obtain a good performance. However, it requires a relatively complex circuit. In this paper, we start with theoretical analysis of electrically small active receiving antenna with non-Foster matching network. At the input port of active network, we can get a negative equivalent input capacitance to obtain an equivalent input gain, which can increase gain of active antenna, sensitivity, and signal to noise ratio (SNR). The experimental results are employed to validate the proposed technique.

2. Non-Foster Matching Analysis of Electrically Small Antenna

2.1. Small Antenna. An electrically small antenna presents a high radiation quality factor Q and an impedance with a large reactance and a small radiation resistance. The theoretical minimum Q of an electrically small antenna for a single mode is expressed as follows:

$$Q = \frac{1}{k^3 a^3} + \frac{1}{ka}, \qquad (1)$$

where k is wave number in free space and a is radius of the smallest sphere enclosing the entire antenna. It is observed from (1) that an electrically small antenna has a higher quality factor. It is a well-known fact that the traditional passive matching antenna has a relatively narrow bandwidth.

The equivalent circuit for an electrically small monopole antenna consists of components of reactance jX_a, radiation resistance R_r, and loss of resistance R_L. The loss R_L of resistance is usually ignored due to its low level. Theoretically,

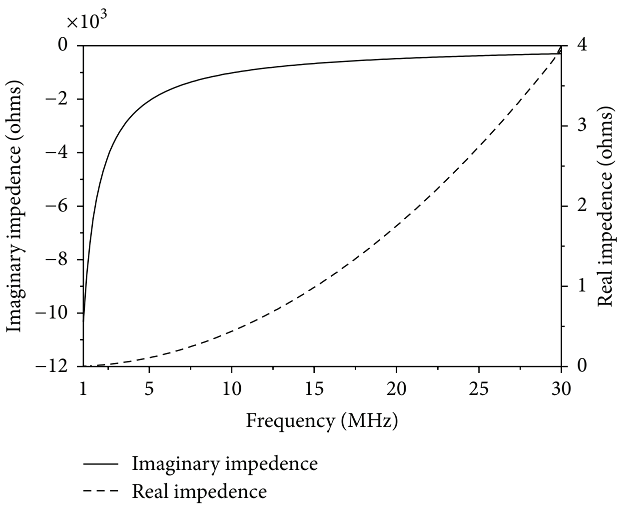


Figure 1: Real and imaginary parts of input impedance of the monopole antenna.

the radiation resistance and reactance for a monopole antenna are expressed as follows:

$$R_r = 40\pi^2\left(\frac{h}{\lambda}\right)^2,$$
$$X_a = 60\left(1 - \ln\frac{h}{b}\right)\cdot\cot\left(2\pi\frac{h}{\lambda}\right), \quad (2)$$

where h and b are the physical length and radius of monopole, respectively. The monopole is 1,000 mm long and its radius is 5 mm. The real and imaginary parts of the monopole antenna input impedance are shown in Figure 1.

2.2. Negative Impedance Convertor Analysis. The traditional active antenna is composed of an electrically small antenna and an active element. This paper investigates the monopole antenna that is directly connected to an FET amplifier, as shown in Figure 2.

The electric field generated at the antenna input port can be expressed as $V_S = Eh_{\text{eff}}$, where E is an electric field strength, and h_{eff} is an effective height. The equivalent capacitance C_a and FET input capacitance C_i of the monopole antenna form a capacitive divider voltage. The input voltage of amplifier is expressed as follows:

$$V_i = V_s\frac{C_a}{C_a + C_i}, \quad (3)$$

where V_i is frequency independent and its bandwidth is dependent on the amplifier property. If C_a increases or C_i decreases, the input voltage may approach to the maximal value. C_i value, limited by an electronic device, is hard to decrease. Increasing the antenna height can degrade C_a unexpectedly. Non-Foster impendence from the negative impedance convertor using a positive feedback capacitor and amplifier can help reduce capacitance of the amplifier, and furthermore get the negative equivalent input capacitance of active network.

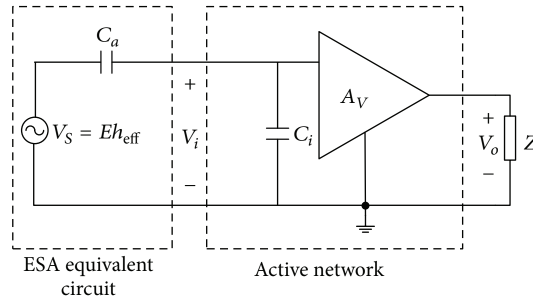


Figure 2: Equivalent circuit of a traditional active antenna.

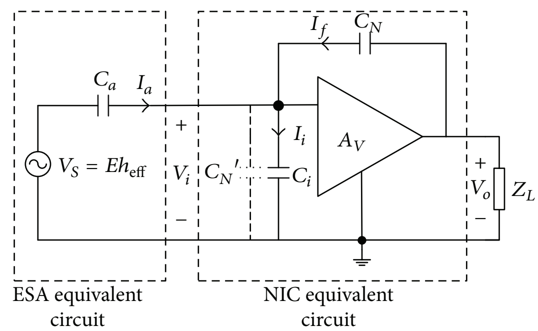


Figure 3: Equivalent circuit of a non-Foster matching electrically small antenna.

The antenna equivalent circuit of an electrically small antenna along with a negative impedance convertor circuit [11] is presented in Figure 3.

In Figure 3, A_V indicates gain of the amplifier voltage; Z_L represents the active antenna load impedance; and C_N denotes the positive feedback capacitor.

By analyzing the circuit in Figure 3, we can get a set of equations as follows:

$$I_a = j\omega C_a\left(V_s - V_i\right),$$
$$I_i = j\omega C_i V_i,$$
$$I_f = j\omega C_N\left(V_o - V_i\right), \quad (4)$$
$$I_i = I_a + I_f,$$
$$V_o = A_v V_i.$$

The active network equivalent input voltage gain is given in the following format:

$$\frac{V_i}{V_s} = \frac{C_a}{C_a + C_i + \left(1 - A_V\right)C_N}. \quad (5)$$

The voltage gain of an active antenna is obtained as follows:

$$\frac{V_o}{V_s} = \frac{C_a}{C_a + C_i + \left(1 - A_V\right)C_N}\cdot A_V. \quad (6)$$

2.3. Equivalent Input Gain Analysis. We use the formulation $C'_N = (1 - A_V)C_N$ to express the negative equivalent capacitance at input port of an active network of a negative impedance convertor. Next, we consider the equivalent input capacitance of an active network $C = C_i + (1 - A_N)C_N$ for different combinations of A_V and C_N. There exist three possibilities: (1) $C > 0$; (2) $C = 0$; and (3) $C < 0$. We discuss the relationship between V_i and V_S for the three cases [12].

(1) $C > 0$. For $|C'_N| < C_i$ in (5), we have $V_i < V_S$, implying that the antenna source voltage cannot be transmitted to the active network and the antenna gain is larger than the traditional active antennas. It is worthwhile to mention that the equivalent input gain in this case is less than 1.

(2) $C = 0$. For $|C'_N| = C_i$ in (5), we have $V_i = V_S$; namely, the active network input voltage is equal to the antenna source voltage, which implies that the input capacitance of the amplifier equals to 0 [11]. This is considered as the non-Foster matching case and its application is limited to improve the antenna gain and SNR [9].

(3) $C < 0$. For $|C'_N| > C_i$ in (5), we have $V_i > V_S$, which allows us to get a negative equivalent capacitance at input port of the active network. The active network input signal is larger than the received signal, which is similar to the enhanced non-Foster matching and useful for improving the efficiency of the antenna gain and SNR [9].

2.4. Stability Analysis. Since the principal ingredient of negative impedance convertor is a positive feedback circuit, we must carry out a stability analysis of the active antenna to derive a stability criterion. Using (5), we can derive a stability condition; for example, $C_a + C_i + (1 - A_V)C_N \neq 0$. Considering the condition of negative impedance convertor, A_V must be satisfied with both $A_v > 1$ and $C_a + C_i + (1 - A_V)C_N > 0$; namely,

$$1 < A_V < 1 + \frac{(C_a + C_i)}{C_N}. \tag{7}$$

If an active antenna works in the status $V_i > V_S$, for $-C_a < C < 0$, we have

$$1 + \frac{C_i}{C_N} < A_V < 1 + \frac{(C_a + C_i)}{C_N}. \tag{8}$$

Equation (8) defines the stability criterion for an active antenna, which implies that A_V must be satisfied with either (7) or (8) in the working frequency band. Outside the frequency band, it must be satisfied with the following criterion:

$$A_V < 1 + \frac{(C_a + C_i)}{C_N}. \tag{9}$$

Equations (8) and (9) are the stable criterions that must be satisfied with designing an active receiving antenna.

2.5. Sensitivity Analysis. Sensitivity is an important indicator for an active receiving antenna, which can be expressed as the equivalent noise field strength of the inherent noise. If $\sqrt{\overline{V}_a^2}$ is the inherent noise of an active receiving antenna, its equivalent noise field strength $\sqrt{\overline{e}_a^2}$ can be expressed as [11]

$$\begin{aligned}\sqrt{\overline{e}_a^2} &= \frac{\sqrt{\overline{V}_a^2}\left[\left(C_a + C_i + \left(1 - A_V\right)C_N\right)/C_a\right]}{h_{\text{eff}}} \\ &= \frac{\sqrt{\overline{V}_a^2}\left[\left(C_a + C\right)/C_a\right]}{h_{\text{eff}}}.\end{aligned} \tag{10}$$

For three cases $C > 0$, $C = 0$, and $C < 0$, $\sqrt{\overline{e}_a^2}$ is taken to be $\sqrt{\overline{e}_{a1}^2}$, $\sqrt{\overline{e}_{a2}^2}$, and $\sqrt{\overline{e}_{a3}^2}$, respectively. From (10), we have

$$\sqrt{\overline{e}_{a1}^2} > \sqrt{\overline{e}_{a2}^2} > \sqrt{\overline{e}_{a3}^2}. \tag{11}$$

It is obvious that the highest active receiving antenna sensitivity is reached for $C < 0$.

3. Design of Active Receiving Antenna

3.1. Design Considerations. The design technique described in the last section is implemented in an active receiving antenna design in the shortwave band. The length and radius of the monopole antenna are 1,000 mm and 5 mm, respectively.

It is important to investigate the receiving sensitivity and nonlinear distortion performance in an active antenna design. When the signal interference of a shortwave antenna is severe, the nonlinear distortion performance becomes especially important and is usually interfered with the second- and third-order intermodulation distortions (IMD) performance. Increasing depth of an active network negative feedback can improve the active antenna nonlinear distortion, and the deeper negative feedback can improve the nonlinear distortion [13]. System noise is closely related to the primary gain. The higher gain of the first level amplifier will improve the system noise and sensitivity. The IMD performance degrades with the cascaded operational amplifiers. With the compromise of parameters, an active receiving antenna with a low noise amplifier and negative impedance converter is shown in Figure 4.

The active antenna in this paper is based on the operational amplifier OPA657, a product of Texas Instruments, due to their better IMD, low noise, JFET-input, high dynamic range, and high gain bandwidth performances. The equivalent circuit of the active receiving antenna is shown in Figure 5.

3.2. Gain and Negative Impedance Analysis. The antenna equivalent capacitance is 15 pF and the amplifier voltage factor is $G = 1 + R_1/R_2$. For the resistance parameters shown

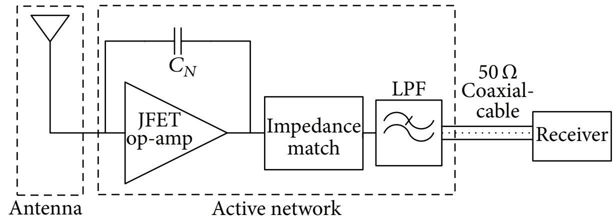


Figure 4: Block diagram of the active antenna.

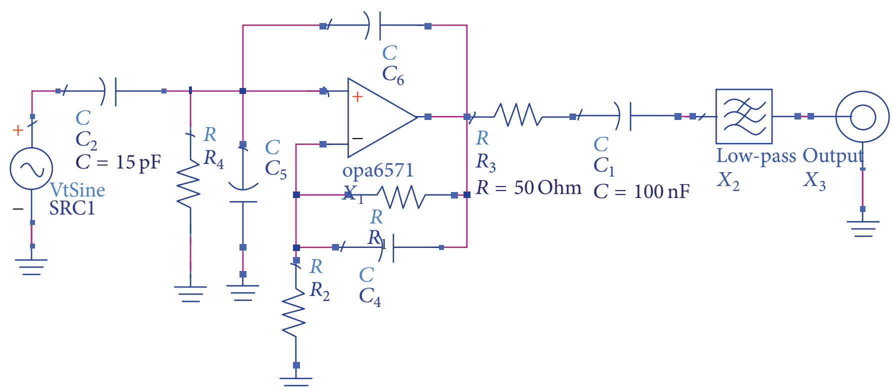


Figure 5: Schematic diagram of equivalent circuit for active receiving antenna.

in Figure 5, the amplifier voltage factor is 4. The operational amplifier voltage gain is expressed in the following format:

$$G_a = 20\log\left[\frac{1}{2}\left(1+\frac{R_2}{R_3}\right)\right]\text{dB}. \quad (12)$$

The operational amplifier voltage gain is 6 dB for a 50-ohm load impedance.

The active network input capacitance C_5 in Figure 5 consists of input capacitance of the amplifier, electromagnetic pulse protection device equivalent capacitance and PCB distributed capacitance. In the absence of negative impedance converter, the active antenna gain is less than 6 dB. By adjusting the feedback capacitance C_N of negative impedance converter, we can obtain an equivalent negative capacitance at the input port of active network and an equivalent input gain, which can achieve an active antenna gain greater than 6 dB.

3.3. Filter Design. Active network bandwidth is determined by the operational amplifier. 200 MHz bandwidth can be achieved and the amplifier voltage factor is 4. The broad bandwidth helps improve the amplifier linearity and bandwidth.

A 13-order Butterworth low-pass filter is shown in Figure 6. To get a flat gain pattern inside 30 MHz bandwidth, 3 dB bandwidth has been designed for about 40 MHz. The simulated S-parameters are shown in Figure 7.

4. Test and Analysis of Active Antenna

The prototype of the active network is shown in Figure 8 and the capacitance of antenna impedance is 15 pF. We investigate the performance of the active antenna below.

4.1. Gain Test. Adjusting positive feedback capacitance can change the equivalent input capacitance of an active network. The variation of active network voltage gain with frequency is shown in Figure 9.

For $C > 0$, the active receiving antenna voltage gain is less than 6 dB in a 50-ohm load impedance. The voltage gain is 6 dB for $C = 0$. However, the active receiving antenna voltage gain is larger than 6 dB for $C < 0$. When the equivalent input capacitance $|C|$ of an active network increases, the equivalent input voltage gain of the active network V_i/V_S also increases. Gain of the active receiving antenna is near 12 dB for $C = -3.7$ pF, and the equivalent input gain is 6 dB. Gain of the active receiving antenna is near 18 dB for $C = -7.5$ pF, and the equivalent input gain is 12 dB. When the equivalent input capacitance $|C|$ is close to C_a, the voltage gain fluctuates considerably, indicating that the antenna stability deteriorates and $|C|$ should not be chosen too close to C_a.

4.2. Voltage Standing Wave Ratio. The voltage standing wave ratio (VSWR) of the active antenna is shown in Figure 10, and it is observed from the figure that VSWR in 100 kHz–30 MHz is less than 1.2, which can be in a good match to the receiver.

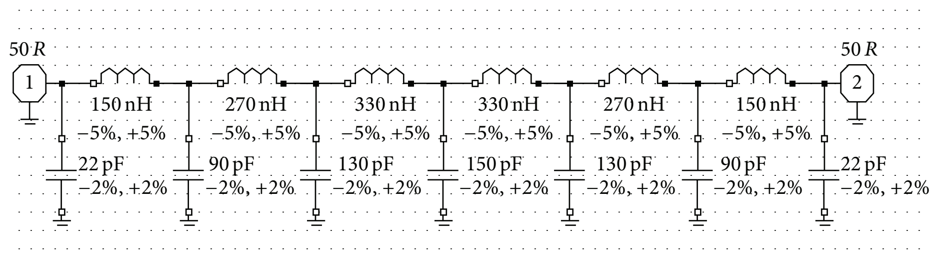


FIGURE 6: Schematic diagram of the low-pass filter.

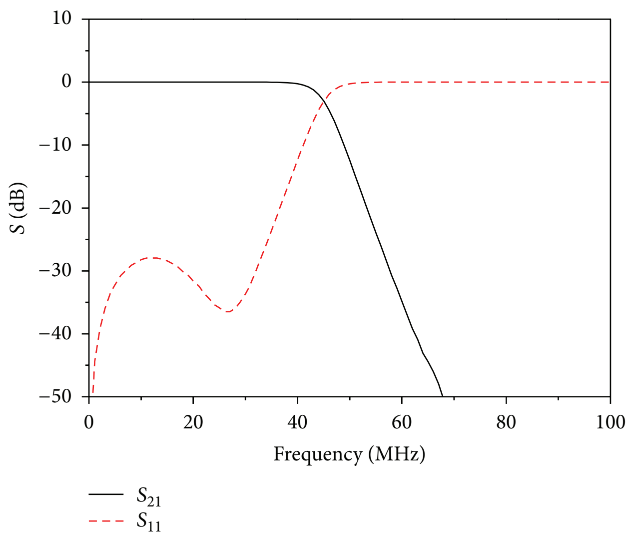


FIGURE 7: *S*-parameters of the low-pass filter.

FIGURE 8: Photograph of the active network.

4.3. Noise Measurement. In the shortwave band, the ambient noise is more severe. The noise figure of active receiving system indicates the active receiving antenna noise performance. The noise of the active receiving system is expressed

$$F_s = 1 + \frac{F_a - 1}{F_A}, \quad (13)$$

where F_A is the ambient noise factor and F_a is the noise factor of the active receiving antenna. Practically, the noise factor of the active receiving system is the ratio of the output SNR of the active antennas to the input SNR; and F_s is usually less than 2.

The noise factor of active receiving system is expressed as

$$F_s = 1 + \frac{V_a^2}{V_A^2}, \quad (14)$$

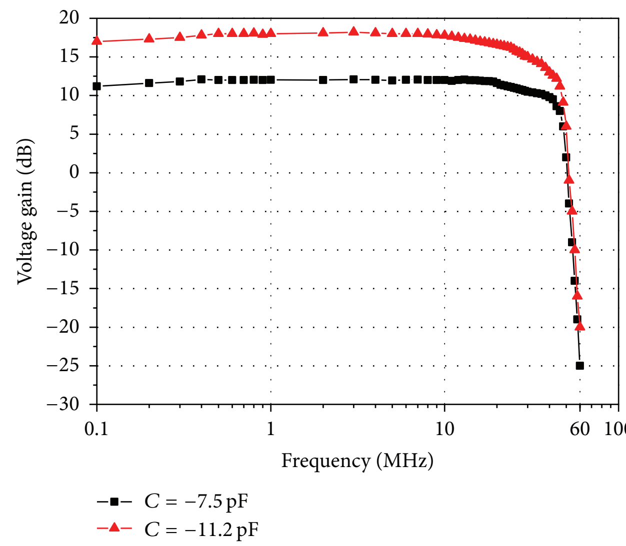


FIGURE 9: Gain variation of the active receiving antenna with frequency.

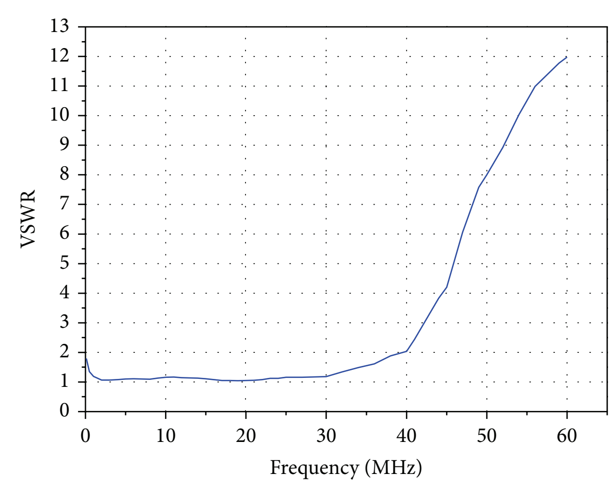


FIGURE 10: VSWR variation of the active antenna with frequency.

where V_a is the output voltage generated by the active antenna noise, and V_A is the output voltage generated by the ambient noise [14].

From (14), we can develop a simple but efficient method to measure the noise factor of an active antenna system, namely,

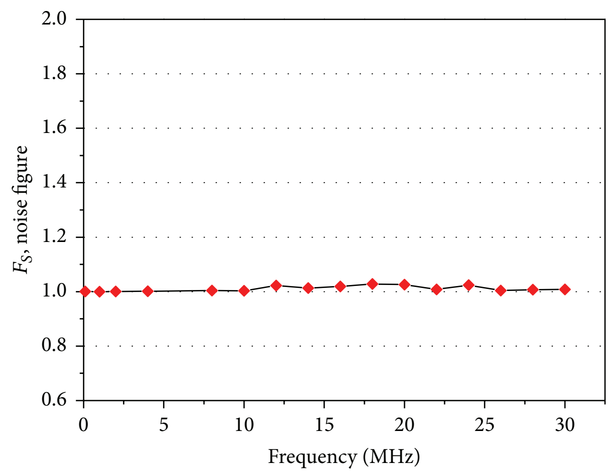


FIGURE 11: Ratio of F_s to the noise factor variation with frequency.

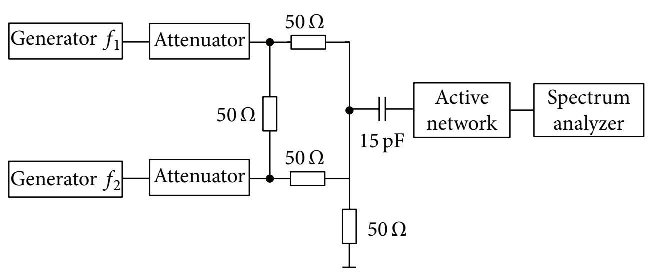


FIGURE 12: Intermodulation distortion measurement configuration.

the inherent noise voltage V_a in an electromagnetic mask room, the noise output voltage V_o in open free space, and the ambient noise voltage V_A. Substituting them into (14), we obtain

$$F_s = 1 + \frac{V_a^2}{V_o^2 - V_a^2}. \tag{15}$$

If the testing receiver noise cannot be ignored, we can measure the inherent noise voltage V_{Ins} of the receiver in an electromagnetic mask room. We can measure the inherent noise voltages $V_1 = V_a + V_{\text{Ins}}$ first in an electromagnetic mask room and the noise output voltage $V_2 = V_o + V_{\text{Ins}}$ of the active antenna second in free space. Then, we can get

$$F_s = 1 + \frac{(V_1 - V_{\text{Ins}})^2}{(V_2 - V_{\text{Ins}})^2 - (V_1 - V_{\text{Ins}})^2}. \tag{16}$$

Using the strategy above, the measurement results are shown in Figure 11, which demonstrate that the ratio of noise of the active receiving system to the noise figure is less than 1.1. The designed antenna in this environment shows a good performance.

4.4. Intermodulation Distortion Measurement. Intermodulation distortion measurement is a very important factor in the broadband active receiving antenna. A typical measurement configuration for IMD in an active receiving antenna is shown in Figure 12.

Intermodulation attenuation of an active receiving antenna is related to the output signal power. The measurement of the second- and third-order intermodulation attenuation is measured for the same inputs and −7.0 dBm of the mutual interference signal output, as shown in Tables 1 and 2.

5. Conclusions

In this paper, we present an analysis and design of an active receiving antenna utilizing negative impedance convertor. We use a low noise operational amplifier to realize the design of active receiving antenna in 100 KHz–30 MHz frequency band. Experimental results demonstrate the negative impedance converter that can improve gain, receiving system sensitivity, and broadband characteristic. The performance of active antenna is closely related to semiconductor technology, and the active antenna design will become more attractive.

Conflict of Interests

This paper does not have a direct financial relation with the commercial identities mentioned in the paper.

Table 1: Second order IMD result.

$f_1 \pm f_2$/MHz	Output signal power/dBm	2nd order IMD/dBc
19 − 12 = 7	−7.0	61.0
11 − 3 = 8	−7.0	60.3
16 − 7 = 9	−7.0	60.7
11 + 3 = 14	−7.0	60.2
7 + 16 = 23	−7.0	59.8
10 + 11 = 21	−7.0	58.6
17 + 7 = 24	−7.0	59.4
19 + 8 = 27	−7.0	57.3

Table 2: Third order IMD result.

f_1, f_2/MHz	Output signal power/dBm	3rd order IMD/dBc
2 ∗ 7 − 8 = 6	−7.0	88.9
2 ∗ 19 − 27 = 11	−7.0	91.2
2 ∗ 20 − 23 = 17	−7.0	90.6
2 ∗ 15 − 9 = 21	−7.0	90.5
2 ∗ 23 − 22 = 24	−7.0	90.1
2 ∗ 10 + 7 = 27	−7.0	87.8
2 ∗ 11 + 8 = 30	−7.0	89.2

Acknowledgment

This paper is supported by the Fundamental Research Funds for the Central Universities.

References

[1] R. A. Sainati and D. E. Fessenden, "Performance of an electrically small antenna amplifier circuit," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 17, no. 1, pp. 88–92, 1981.

[2] A. Harris and G. Myers, "An Investigation of Broadband Miniature Antennas," Tech. Rep., Naval Postgraduate School, Monterey, Calif, USA, 1968.

[3] A. Perry, *Broadband antennas systems realized by active circuit conjugate impedance matching [M.S. thesis]*, Naval Postgraduate School, Monterey, Calif, USA, 1973.

[4] C. White, J. Colburn, and R. Nagele, "A non-foster VHF monopole antenna," *IEEE Antennas and Wireless Propagation Letters*, no. 11, pp. 584–587, 2012.

[5] E. Ugarte-Munoz, S. Hrabar, and D. Segovia-Vargas, "Stability of non-foster reactive elements for use in active metamaterials and antennas," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 7, pp. 3490–3494, 2012.

[6] S. Koulouridis, "Non-Foster design for antennas," in *Proceedings of the IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting (APSURSI '11)*, pp. 1954–1956, Spokane, Wash, USA, July 2011.

[7] R. M. Rudish and S. E. Sussman-Fort, "Non-foster impedance matching improves S/N of wideband electrically-small VHF antennas and arrays," in *Proceedings of the 2nd International Conference on Antennas, Radar, and Wave Propagation (IASTED '05)*, pp. 318–323, Banff, Canada, July 2005.

[8] S. E. Sussman-Fort and R. M. Rudish, "Non-foster impedance matching of electrically-small antennas," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 8, pp. 2230–2241, 2009.

[9] S. E. Sussman-Fort, "Non-foster vs. active matching of an electrically-small receive antenna," in *Proceedings of the IEEE International Symposium on Antennas and Propagation and CNC-USNC/URSI Radio Science Meeting—Leading the Wave (AP-S/URSI '10)*, pp. 1–4, Toronto, Canada, July 2010.

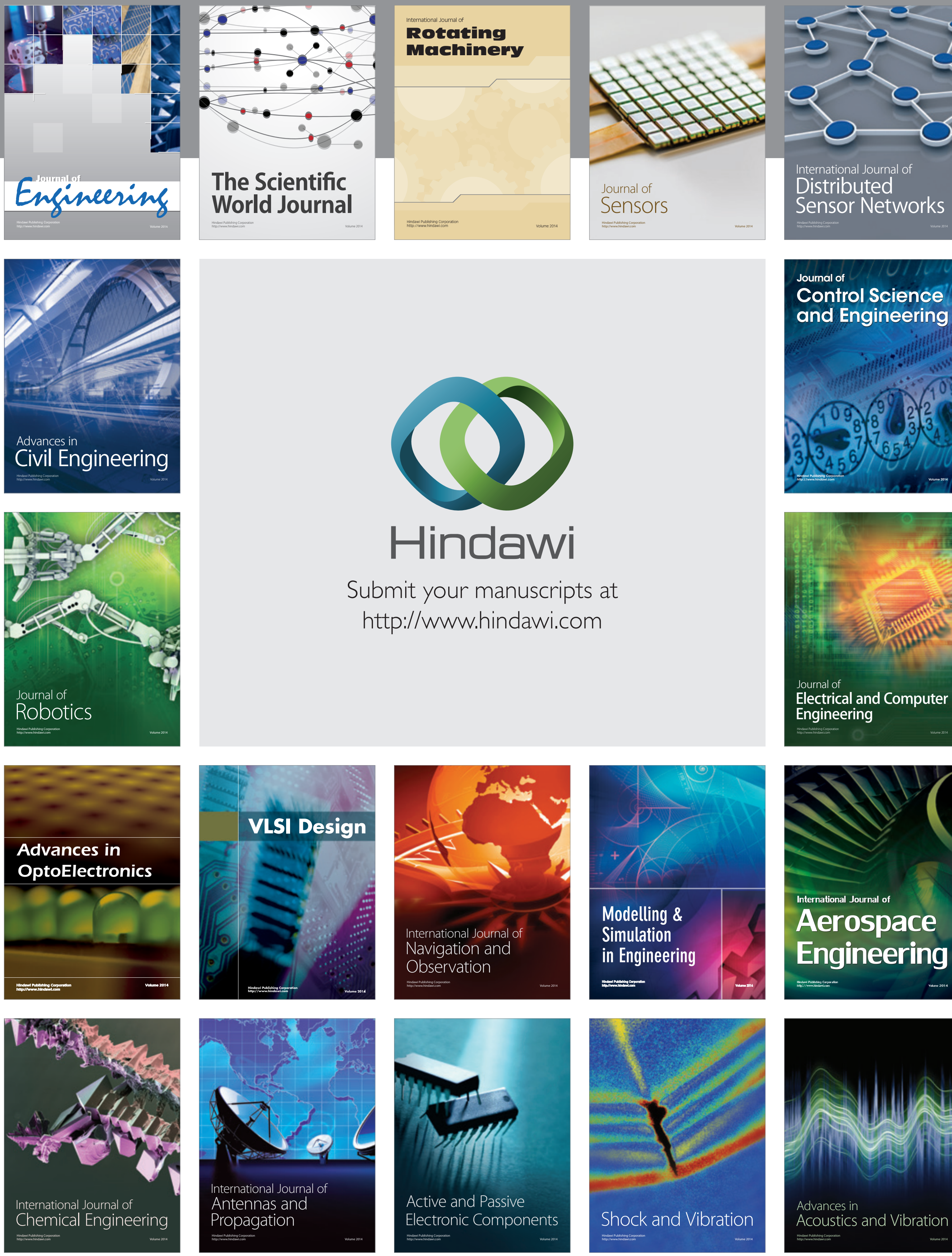
[10] J. T. Aberle, "Two-port representation of an antenna with application to non-foster matching networks," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 5, pp. 1218–1222, 2008.

[11] W. Li, "New method for designing active antenna," *Acta Electronica Sinica*, vol. 21, no. 7, pp. 110–113, 1993.

[12] W. Li, R. Chen, N. Zai, and S. Li, "Wideband matching of an electrically small antenna using a negative impedance converter technique," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, pp. 1–2, Chicago, Ill, USA, 2012.

[13] W. Li, "1. 5 MHz to 30 MHz broadband short-wave active receiving antenna," *Harbin Ship Engineering Institute Academic Journal*, vol. 10, no. 1, pp. 81–86, 1989.

[14] W. Li, "Noise analysis and measurement of active antenna," in *Proceedings of the 7th International Symposium on Antennas, Propagation and EM Theory (ISAPE '06)*, pp. 138–141, October 2006.



Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
International Journal of Distributed Sensor Networks
Advances in Civil Engineering
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration