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DESIGN AND INVESTIGATION OF BROADBAND MONOPOLE ANTENNA LOADED WITH NON-FOSTER CIRCUIT

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Abstract—The possibility of using non-Foster circuit to expand the bandwidth of a monopole antenna is investigated theoretically. Beginning with an inductor-loaded monopole antenna resonating at different frequencies by changing the value of the loaded inductor, we show that a frequency-dependent inductor is needed to enhance the bandwidth of the monopole antenna. The curve for the reactance of the frequency-dependent inductor versus frequency is fitted, which enlightens us to use a non-Foster reactive circuit to realize the frequency-dependent inductor. Based on the above studies, a monopole antenna loaded with a non-Foster circuit is presented. Simulated results demonstrate that the input reactance of the loaded antenna becomes stable and approaches zero, which favors the impedance matching and extends the bandwidth to a certain extent. Finally, a passive (Foster) matching circuit is designed to improve the bandwidth further. A 0.69-m monopole antenna with 2.0:1 VSWR in the frequency range 30–150 MHz is designed and investigated.

1. INTRODUCTION

With the rapid development of modern wireless communication technologies, there has been an extensive demand to design an antenna with relatively stable impedance and radiation pattern over a wide frequency range. Meanwhile, because of the market pressures for miniaturizing communication devices, it is necessary to study the methods to reduce the dimensions of antennas. In order to realize

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these requirements, the loaded monopole antennas, which use one or more internal lumped elements, were then introduced [1]. Changing the positions where the lumped elements loaded or the values of the lumped elements, the antenna current distribution and radiation pattern are changed, and then wideband behavior may be obtained. For instance in [2], a monopole antenna was loaded with several lumped elements composed of R, L, and C in different positions along the radiator. The bandwidth was extended and the dimension was reduced, but the efficiency got lower over the whole frequency range. In [3], the relationship between bandwidth and efficiency has been presented. It is shown that the improvement in bandwidth is achieved at the cost of lower efficiency for an electrically-small antenna. In fact, even if this antenna could achieve an optimal efficiency over the wide frequency range, its bandwidth could not break through the Chu limit [4].

To surpass the Chu limit for electrically-small antennas, non-Foster matching networks were proposed and studied. Sussman-Fort and Rudish in [5] had presented the technique of non-Foster impedance matching, which employed active networks of negative inductors and capacitors to bypass the restrictions of gain-bandwidth theory. And in [6] a work for the non-Foster impedance matching of electrically-small dipoles and its experimental results were presented. As compared to passive matching, non-Foster circuit can achieve wider bandwidth matching and significantly greater efficiency over a given bandwidth. However, it does not change the antenna current distribution and radiation pattern. It is believed that a study on the radiator of the monopole antenna loaded with the non-Foster circuit is significant.

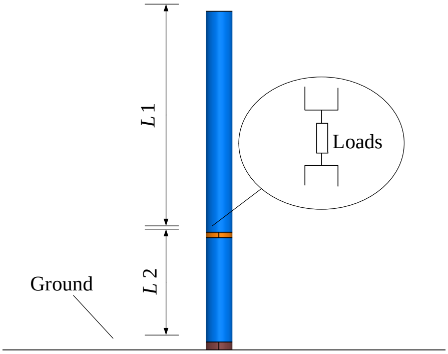


Figure 1. The loaded monopole antenna.

In this paper, a monopole antenna with a length less than $\lambda/4$ is introduced. Because this monopole antenna is capacitive, a compensatory inductor is usually utilized to obtain real input impedance (resonance). When the value of this inductor is changed, the antenna will resonate at different frequency. From these results, it is considered that if non-Foster circuit is used to load the monopole antenna, the antenna will fulfill resonances over a broad frequency range when the non-Foster circuit is properly designed.

2. SIMULATION OF THE MONOPOLE ANTENNA

Figure 1 shows the monopole antenna loaded with a lumped circuit element, which is located on a ground plane with dimensions of $1.25\lambda \times 1.25\lambda$ perpendicularly. The antenna length and radius are 0.23λ and 0.017λ, respectively, where $\lambda = c/f$, c being the speed of light in vacuum and f being its resonant frequency 100 MHz.

First, the antenna is simulated without the loading circuit by Ansoft HFSS (simulation software based on the finite element method) from 30 MHz to 125 MHz. The monopole antenna resonators and ground in the simulation are treated as lossless for simplifying purpose. The simulated VSWR with a 50 Ω source is shown in Figure 2. The minimum VSWR of this monopole antenna appears at 100 MHz with a value of 1.18. It is clearly seen that the VSWR at the low frequency range of 30–85 MHz are not acceptable, although the VSWR at the

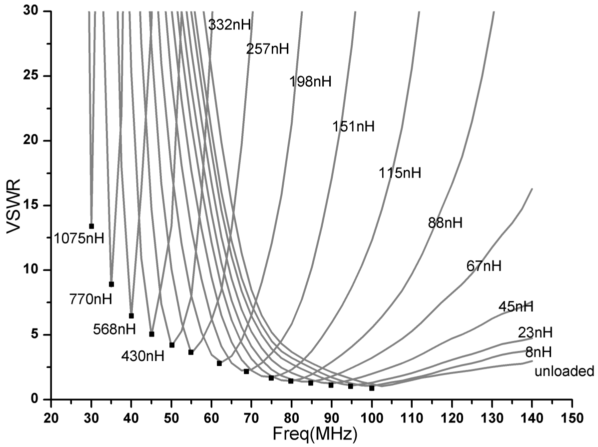


Figure 2. The VSWR of the loaded monopole antenna at different resonant frequency varying with the value of the inductor.

high frequency range of 85–125 MHz are relatively small (i.e., that the monopole without loading circuit is a narrow-band antenna), which is due to the fact that the monopole antenna is capacitive when its electrical length is less than $\lambda/4$. The capacitive characteristics, especially at the lower frequencies, are stronger, which means that the antenna can not radiate energy at the low frequency band efficiently due to its bad impedance matching. In general, the bandwidth is getting narrower and the value of Q is getting higher when the dimensions of the antenna are smaller [7].

In [1], loads are introduced to broaden the bandwidth of a wire antenna. In order to find out the influence of the loaded elements on the monopole antenna shown in Figure 1 clearly, the antenna is loaded in only one position with one lumped element, an inductor. The loaded inductor is modeled as ideal lossless component. The distance between the loaded element and ground plane is $L2$, and the loaded element spaces $L1$ apart from the top of the antenna. $L1$ is 200 mm and $L2$ is 490 mm. By the way, $L1$ and $L2$ are selected by considering the realizability of the negative capacitor and negative inductor as mentioned later.

When different values of the loaded compensatory inductor are given, the loaded monopole antenna will resonate at different frequencies. A set of 14 different values of the loaded inductor are chosen to make the antenna resonate at 30, 35, 40, 45, 50, 55, 60,

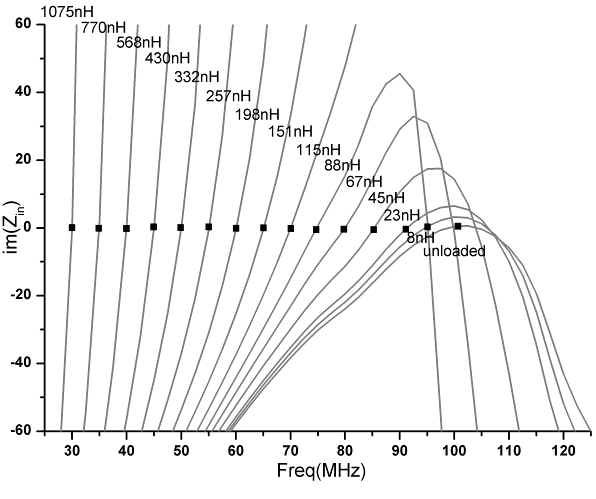


Figure 3. The input reactance of the loaded monopole antenna at different resonant frequency varying with the value of the inductor.

65, 70, 75, 80, 85, 90, and 95 MHz. The corresponding relationship between them is give in Table 1, and the curves of the VSWR and the input reactance varying with the different values of inductor are shown in Figures 2 and 3.

The loaded inductor is ideal lossless element, its reactive value X at the resonant frequency can be derived by $X = \omega L$. If more frequency points are chosen between 30–95 MHz, more values of the loaded inductor will be obtained. By fitting these frequency points, the curve of the needed reactive value of the loaded inductor versus the resonant frequency is given in Figure 4.

It is noted that if the reactive value of a loaded element changes just as the curve shown in Figure 4, the monopole antenna will resonate over a wide frequency range. However, such an element is not easy to find because in Figure 4 the slope of the curve is negative. Generally speaking, the commonly used lumped elements like L and C are Foster elements. The most remarkable characteristic of these elements is that the slope of their frequency characteristic is positive. Under this condition, a simple Foster load limits the possibility of broadening the

Table 1. The value of the inductor at different resonant frequency.

f_r (MHz)	30	35	40	45	50	55	60	65	70	75	80	85	90	95
L (nH)	1075	770	568	430	332	257	198	151	115	88	67	45	23	8

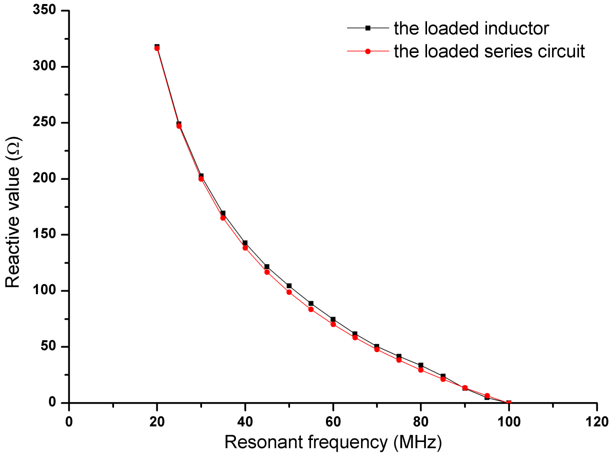


Figure 4. The needed reactive value of the loaded inductor at different resonant frequency and the reactive value of the loaded non-Foster circuit.

bandwidth of an antenna, as mentioned in [8]; in order to broaden the bandwidth, Boag et al. in [2] introduced a series of Foster loads, however, this means not only has increased the complexity of the antenna, but also has reduced the efficiency. The most important is that, under the condition of the Foster loading, the bandwidth of the wire antennas is limited by the Chu limit. Oppositely, the slope of the frequency curve of non-Foster element is negative. Using the non-Foster elements, a circuit can be synthesized to provide the similar reactive values indicated in Figure 4. Then the monopole antenna can resonate over a wider frequency range if the Foster element is replaced by the non-Foster circuit.

In order not to increase the complexity or reduce the efficiency of the monopole antenna significantly, the number of the loaded non-Foster elements is used as few as possible. Based on the observation and analysis of the needed reactive curve of the loaded inductor shown in Figure 4, the reactive curve of the non-Foster circuit constructed with a negative capacitor could fit it approximately. For the purpose of accuracy, the form of the non-Foster circuit constructed with a negative inductor L and a negative capacitor C in series is adopted to produce the desired frequency dependent reactance. The series circuit is shown in Figure 5.

The values of non-Foster L and C can be expressed as following:

$$\frac{1}{j2\pi f_1 C} + j2\pi f_1 L = Z_1 \tag{1}$$

$$\frac{1}{j2\pi f_2 C} + j2\pi f_2 L = Z_2 \tag{2}$$

where $f_1 = 20\,\text{MHz}$ and $f_2 = 100\,\text{MHz}$. Z_1, Z_2 are, respectively, the needed reactive value of the loaded inductor at the resonance frequency f_1 and f_2. According to Equations (1) and (2), the values of the non-Foster elements which are used to produce the frequency characteristic

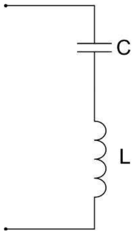


Figure 5. The negative lumped element circuit.

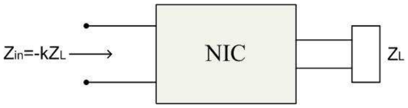


Figure 6. Negative impedance converter ($k > 0$).

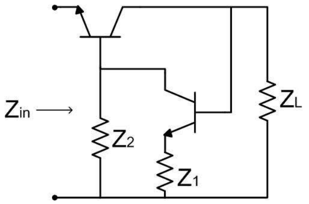


Figure 7. Linvill's ideal NIC.

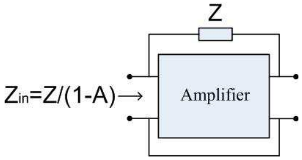


Figure 8. Amplifier-based NIC.

shown in Figure 4 are

$$L = -105.4\,\mathrm{nH} \quad C = -24.1\,\mathrm{pF}$$

We use HFSS to simulate the predicted reactive values of the loaded non-Foster circuit. The results are shown in Figure 4. It is found that the curves of the reactive value of the loaded non-Foster circuit and the needed reactive value of the loaded inductor shown in Figure 4 fit accurately.

In addition, the negative inductor and negative capacitor can be realized by terminating a two-port element called negative impedance converter (NIC) shown in Figure 6. A practical transistorized NIC is shown in Figure 7, which was designed and tested in [9–11]. An alternative NIC, shown in Figure 8, is realized using amplifier [12].

3. ANALYSIS OF THE RESULTS

3.1. Impedance Analysis

The contrast of input reactance and input resistance with and without non-Foster circuit are illustrated in Figures 9 and 10, respectively. The figures show that without the non-Foster circuit, the character of the antenna is capacitive and the radiant resistance is so small that the energy concentrating near the antenna could not be radiated out. After the non-Foster circuit is loaded, the magnitude of the reactance of the antenna is smaller than the unloaded over a wide frequency range, as well as varies more gently with frequency. This behavior implies that it is easier to match the non-Foster loaded monopole antenna than the unloaded monopole antenna. As expected, the non-Foster circuit loading yields the best possible frequency bandwidth performance.

The variation of the VSWR versus frequency is depicted in Figure 11. The improvement in the input impedance bandwidth using non-Foster circuit is clear. It is shown that the bandwidth for VSWR$<$ 3 is 2.3:1 (65–150 MHz), while the bandwidth of the unloaded monopole antenna is only 1.5:1 (85–130 MHz). It is worth notice that

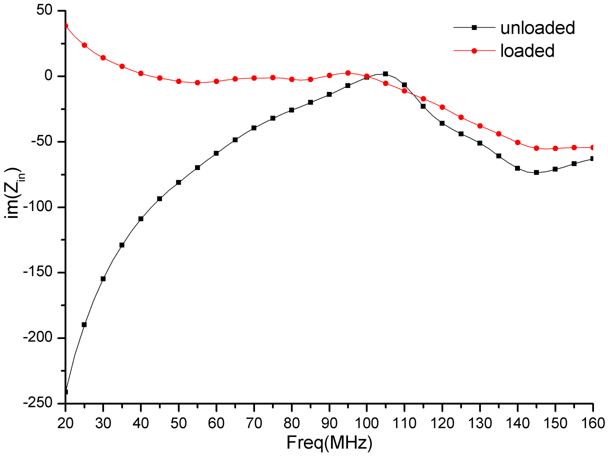


Figure 9. The value of the input reactance with and without the non-Foster circuit loading.

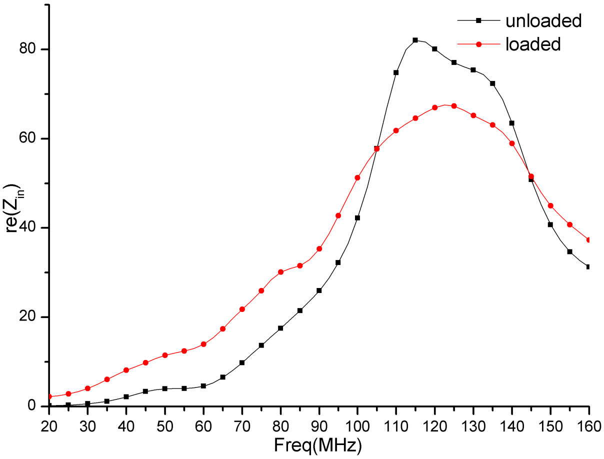


Figure 10. The value of the input resistance with and without the non-Foster circuit loading.

the VSWR between 30–65 MHz is improved remarkably, although the maximum value is 14.5. This is because among the frequency range of 30–65 MHz the input resistance (shown in Figure 10) is too small.

Based on the non-Foster circuit loading, the bandwidth can be enhanced further by using a passive matching network at the feed port. In fact, according to the results outputted from the self-developed optimization algorithm based software which is designed to calculate matching network, the passive matching network is obtained and used. The improved VSWR is shown in Figure 11.

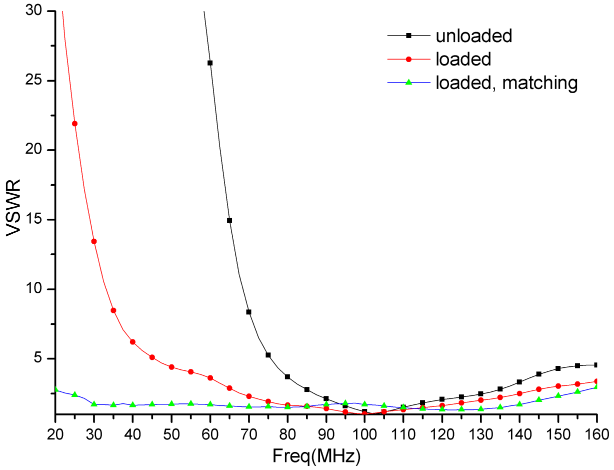
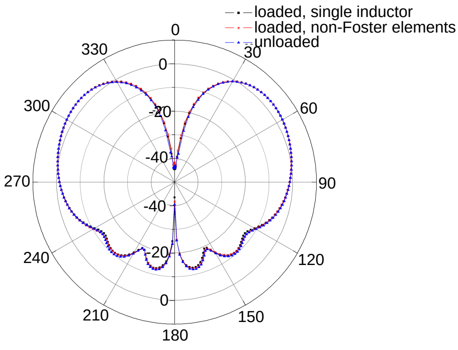


Figure 11. The VSWR of the unloaded monopole antenna and the loaded monopole antenna with and without the passive matching network.



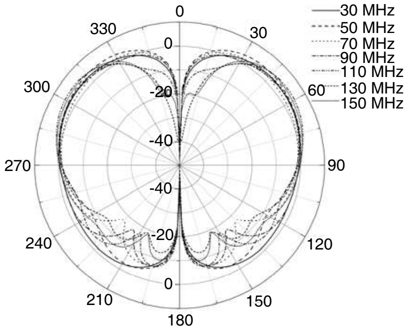


Figure 12. The radiation pattern of the unloaded and loaded monopole antenna.

Figure 13. The radiation pattern of the loaded monopole antenna at different frequency.

3.2. Radiation Pattern Analysis

Among all the characteristics of an antenna, the radiation pattern is one of the most important ones. The radiation pattern of the unloaded, the inductor loaded and the non-Foster loaded antenna at 80 MHz is shown in Figure 12, respectively. It is clear that the radiation patterns are stable. Here it is also noticeable that when the antenna is unloaded, its length is 0.83 m, and when the antenna is loaded with one inductor or the non-Foster circuit, the length of the antenna becomes 0.69 m. So not only the radiation pattern maintain stable, the dimensions of the antenna get smaller when the non-Foster circuit is employed. Compared with the unloaded antenna, the radiation patterns between 30–150 MHz which are shown in Figure 13 stay acceptable as well.

4. CONCLUSION

In this paper, a new design methodology is introduced to broaden the bandwidth of the monopole antennas. This method employs a non-Foster circuit to neutralize the input reactance of an antenna and change the current distribution over a wide frequency range. Based on this, the antenna resonates over a wide frequency band. A monopole antenna loaded with a non-Foster circuit is presented. It is found that the loaded non-Foster circuit is efficient in improving the overall bandwidth of the proposed monopole antenna. The radiation pattern of the loaded antenna is stable over a wider frequency range compared to the unloaded one. Also its dimensions are smaller than the unloaded antenna. In addition, the bandwidth of the non-Foster loaded monopole antenna can be improved further when a passive matching network is introduced at the feed port. Antennas with more complicated structures and multi-loads will be studied and reported in the future.

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