Postprint: A Design for Improving Low-Frequency Thin-Film Antennas on the Lunar Surface Using Non-Foster Matching Circuits

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Abstract

Lunar low-frequency radio observations hold tremendous potential for scientific discoveries and are expected to unveil the secrets of the cosmic dark ages and dawn era. This paper proposes a novel design scheme for antennas and their matching circuits for low-frequency observations on the lunar far side, utilizing non-Foster matching circuits to significantly reduce the antenna' s physical size, making it lightweight and convenient for lunar surface deployment. First, a lightweight, wide-temperature-range, easily extensible, foldable electrically small film antenna convenient for lunar surface deployment was designed, which exhibits excellent omnidirectional characteristics, with a gain of less than 1.92 dB and a half-power beamwidth greater than 83° within the 4–8 MHz band. Then, non-Foster matching circuits were employed to improve its impedance performance, optimizing the antenna' s reactance from as high as -985.3 Ω to within -16.5 Ω. Finally, impedance and noise measurements were conducted using an equivalent circuit, with its noise power density level being less than -150 dBm/Hz across most of the frequency range, thereby confirming the feasibility of this scheme.

Full Text

An Application of Non-Foster Matching Circuit in Improving Lunar Low-Frequency Membrane Antenna

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Abstract

Low-frequency radio observations on the lunar surface hold tremendous potential for scientific discovery and may unveil the secrets of the cosmic dark ages and dawn. This paper proposes a novel design scheme for antennas and matching circuits for low-frequency observations on the lunar far side, utilizing a non-Foster matching circuit to substantially reduce the antenna' s physical size, making it lightweight and easy to deploy on the lunar surface. First, we designed a lightweight, electrically small membrane antenna with a wide temperature range, high ductility, and foldability for convenient lunar deployment. The antenna exhibits excellent omnidirectionality, with gain less than 1.92 dB and half-beamwidth greater than 83° within the 4–8 MHz band. Next, a non-Foster matching circuit was employed to improve its impedance performance, optimizing the antenna reactance from as high as -985.3 Ω to within -16.5 Ω. Finally, impedance and noise measurements were conducted using an equivalent circuit, demonstrating a noise power density level below -150 dBm/Hz across most of the frequency range, thereby confirming the feasibility of the proposed scheme.

Keywords: low-frequency radio astronomy; lunar-based astronomical observation; membrane antenna; electrically small antenna; non-Foster matching circuit

0 Introduction

To date, human observations of the universe have achieved nearly complete coverage across most electromagnetic bands. However, below 10 MHz, ground-based observations are extremely difficult due to ionospheric refraction, absorption, and reflection of electromagnetic waves, as well as substantial electromagnetic interference from radio equipment. In contrast, the lunar far side offers an exceptionally clean electromagnetic environment, as the Moon can block electromagnetic radiation from Earth. Consequently, low-frequency radio astronomy has become widely recognized as one of the most important scientific endeavors to be conducted on the lunar surface, particularly on the far side. Internationally, preliminary research in this area is already well underway, with several major proposals emerging, such as FARSIDE and LCRT in the United States and ALO in Europe [1-3].

Transporting equipment to the Moon entails high costs, necessitating the development of lightweight antennas and receiving systems for low-frequency radio observations on the lunar far side. Given the absence of atmosphere on the lunar surface and the low conductivity of lunar regolith, membrane antennas may be particularly suitable for lunar radio observations. We propose a method of deploying membrane antennas on the lunar far side for ultra-long wavelength signal observation. However, since wavelengths in this band can reach tens of meters to kilometers, conventional half-wave dipole designs would require correspondingly large antenna sizes. Although membrane antennas can be rolled for transport, the width is constrained by the storage spool, resulting in a narrow strip-shaped antenna with limited operating bandwidth that cannot achieve broadband matching.

To achieve a larger observation bandwidth, electrically small antennas with dimensions smaller than the wavelength can be employed. Such antennas also offer excellent omnidirectionality. However, electrically small antennas inherently have small radiation resistance and large reactance, leading to high radiation quality factors that make them difficult to match with transmission lines and hinder efficient power transfer, thereby affecting system sensitivity [4][5]. Under these conditions, traditional passive matching networks constrained by gain-bandwidth product theory cannot achieve broadband performance [6][7]. Using the electrically small antenna designed in this paper as an example, we select the impedance at the optimal point within the entire band (10 MHz) to illustrate the problem: if broadband matching is impossible even at the best impedance point, it is even less feasible at lower frequencies. Substituting ω_1 = 3 MHz, ω_2 = 10 MHz, ω_0 = 6.5 MHz, R = 33 Ω, and C = 93 pF into the Bode-Fano constraint formula (1) for electrically small antennas, $|\Gamma(\omega)|\ d\omega \leq \pi RC$, yields $|\Gamma| \geq 0.944$. This indicates that even the ideal broadband matching result is very poor within the 3–10 MHz bandwidth.

In contrast to traditional passive matching networks, non-Foster matching can overcome gain-bandwidth limitations by canceling the antenna's large reactance and substantially improving the impedance performance of electrically small antennas, thereby increasing operating bandwidth [8].

Non-Foster matching breaks the constraints of Foster' s theorem, also known as the reactance theorem [9], which applies to lossless passive element networks. In such two-port networks, the input reactance increases with frequency, as shown in formula (2): $X(\omega)/\ \omega > 0$ and $B(\omega)/\ \omega > 0$, where X represents reactance, B represents susceptance, and ω is frequency. Conventional capacitors and inductors are Foster elements whose reactance is a monotonically increasing function of frequency. Conversely, if an element' s reactance decreases with increasing frequency, it is called a non-Foster element. Generally, non-Foster elements have negative impedance values. Unlike positive-value elements that consume power, non-Foster elements actually generate power, which is impossible for passive components. Therefore, non-Foster elements are realized through active circuits called Negative Impedance Converters (NIC). Non-Foster matching essentially uses NIC circuits to convert capacitors and inductors into negative capacitors and negative inductors to cancel the antenna' s equivalent reactance.

As early as 1954, Linvill applied NICs to active filter design [10]. Harries & Myers (1968) subsequently applied non-Foster elements to antennas, demonstrating significantly improved performance after loading non-Foster matching networks [11]. Since then, numerous studies have investigated improving electrically small antennas using non-Foster matching networks, with recent applications documented in references [12-13].

This paper proposes a design for an electrically small membrane antenna loaded with a non-Foster matching network for lunar-based low-frequency radio astronomy observations in the 3-10 MHz range. We completed simulations and hardware fabrication for both the antenna and the non-Foster matching network, and conducted measurements using an antenna equivalent circuit. The results demonstrate that the non-Foster circuit substantially reduces the reactance of the electrically small membrane antenna, improves antenna performance, and validates the feasibility of the overall scheme.

1 Antenna Design

The polyimide membrane antenna consists primarily of copper foil on the upper layer and polyimide film material on the lower layer. With its wide temperature range (-200°C to 300°C), stability, light weight (density 1.42 g/cm^3), and rollable/deployable characteristics, it has broad applications in aerospace and is highly compatible with our proposed scheme, making it very suitable for lunar surface use.

The antenna is expected to be deployed on the lunar surface by a rover carrying an antenna spool. The antenna width is limited by the spool width. Here we select a width of 25 cm, which is much smaller than the wavelength, making its performance similar to that of a whip antenna. For electrically small antennas, changes in shape have minimal impact on performance. We adopted a butterfly-shaped membrane antenna with a simple structure that is easy to deploy. Spherical caps were loaded at the ends to reduce antenna tip effects, and the overall structure has a tapered design that is simple to fabricate with relatively smooth impedance characteristics. The structural diagram is shown in [Figure 1: see original paper].

The antenna’ s design dimensions determine its equivalent impedance. Non-Foster circuits are sensitive and potentially unstable, requiring specific design for each antenna. Additionally, non-Foster circuits have certain limitations that impose constraints on applicable antennas. Therefore, antenna and non-Foster matching circuit design must be performed synergistically.

It would be convenient if the antenna impedance could be approximated by a single passive component value, as this would reduce the number of components needed in the non-Foster circuit design and avoid associated parasitic effects. However, the antenna’ s reactance cannot be completely fitted by a single capacitor. As shown in [Figure 2: see original paper], the equivalent capacitance of the antenna’ s imaginary part gradually increases with frequency. Therefore, we adopted a series capacitor-inductor combination to fit the antenna impedance and performed co-simulation using HFSS and ADS software.

The simplest way to ensure non-Foster circuit stability is to maintain the antenna reactance as either always positive or always negative within the operating band. For our antenna, this means ensuring the imaginary part remains capacitive (negative reactance) throughout the operating band, which imposes certain constraints on the maximum antenna size.

Based on the above requirements, the final antenna dimensions are determined as follows, where L1 and L2 are the lengths of the feed end and overall antenna, and W1 and W2 are the widths at the feed end and tip:

Antenna dimensions

To ensure simulation accuracy, we used HFSS and CST for optimization and simulation. Both software packages offer high accuracy for electrically small antenna simulation and can cross-validate each other. The antenna impedance is shown by the curve labeled "original" in [Figure 3: see original paper]. The figure shows that the impedance is poor across the entire band and difficult to match with a 50 Ω transmission line. Within the operating band, the imaginary part is consistently negative, while the real part is generally small. The real part characteristics are similar to those of an electrically small whip antenna, with resistance proportional to the square of frequency. This reveals an important issue: even though we later use non-Foster circuits to reduce the antenna' s imaginary part, the real part still differs from 50 Ω. Transformers or matching networks could adjust the real part, or some loss could be intentionally introduced, but this would affect antenna gain and requires trade-off considerations.

[Figure 3: see original paper] shows the antenna impedance and impedance after non-Foster loading.

Antenna impedance and impedance after non-Foster loading

[Figure 4: see original paper] shows the antenna' s linear radiation pattern in an ideal environment. As this antenna is electrically small, its pattern resembles that of a standard short dipole with excellent omnidirectionality.

2 Non-Foster Circuit Design

Non-Foster circuits exhibit negative reactance slope, opposite to the trend of conventional passive components whose reactance increases with frequency. This breaks the gain-bandwidth product limitation and enables cancellation of the large reactance of electrically small antennas within a certain frequency range.

This paper designs a floating voltage-inversion non-Foster circuit based on transistor amplifiers. The schematic is shown in [Figure 5: see original paper], where two transistors are connected in a feedback configuration to invert the voltage across load Z_L and drive current from lower to higher potential as active devices, resulting in the non-Foster circuit's terminal impedance being the negative of the load impedance.

[Figure 5: see original paper] Non-Foster schematic and transistor equivalent circuit

First, we assume load impedance Z_L is in series with port b on the right side of the equivalent circuit. If the non-Foster circuit converts load impedance Z_L to -Z_L, the input impedance looking into port a from the left would be 0 Ω, meaning the non-Foster matching circuit successfully cancels the load impedance. Using nodal analysis, we obtain the following equations:

$$i_a' = -i_a$$

$$-g_m v_b + g_m v_a + (g_m - \frac{1}{r_e})v_c + (\frac{1}{r_e} - g_m)v_c' = 0$$

$$Z_{in} = \frac{v_a}{i_a} = 2g_m r_e Z_L - 2Z_L - 2r_e$$

where $g_m r_e = 1$, and the transistor transconductance g_m approaches infinity, so $Z_{in} \to 0$.

In the overall circuit design, transistor amplifier selection is critical, as it is the primary noise source in the circuit. Therefore, low-noise transistors should be selected. After comprehensive consideration, we chose the NE68133 as the active device for negative impedance conversion. Based on the datasheet, we selected a bias condition of $I_c = 10$ mA and $V_{ce} = 8$ V, then calculated the bias resistor values. The circuit diagram is shown below, where R_d and R_b serve as voltage divider resistors, R_s as a feedback resistor, C as a DC blocking capacitor, L_d as an RF choke, C_f as a voltage inversion capacitor, and C_x, L_x as loads for negative impedance conversion. Together with power supply decoupling circuits, these components form the non-Foster circuit. Component values are listed in the table below:

[Figure 6: see original paper] Circuit structure diagram

Circuit component values

Considering that low-frequency antennas are strongly affected by their environment and impedance testing is difficult, we used capacitor-inductor circuits to simulate the antenna’ s impedance characteristics for convenient debugging. When the antenna impedance characteristics resemble those of an electrically small whip antenna, it is difficult to completely fit the antenna simulation circuit using low-order series-parallel component configurations, while increasing component count introduces parasitic effects that are difficult to characterize. After extensive simulation and debugging, we finally determined a combination of 36 pF capacitor in series with 4.3 H inductor. The curve labeled “non-Foster” in [Figure 3: see original paper] shows the impedance simulation after loading the non-Foster circuit.

The figure shows significant improvement in the imaginary part with minimal introduced loss in the real part. The simulation results demonstrate that loading the non-Foster circuit substantially enhances the impedance performance of the electrically small butterfly membrane antenna.

3 Prototype Fabrication and Testing

After finalizing the dimensions, we fabricated the antenna prototype using flexible printed circuit board technology, which ensures good precision even for larger sizes. The circuit measures 47 mm × 31 mm, with FR4 substrate material (relative permittivity 4.4, thickness 0.8 mm). Photographs of the fabricated antenna and non-Foster circuit are shown in [Figure 7: see original paper] and [Figure 8: see original paper].

[Figure 7: see original paper] Antenna physical diagram
[Figure 8: see original paper] Circuit physical diagram

A balun was inserted between the antenna and circuit. We conducted measurements in different environments: ground (concrete, red line), roof (building rooftop platform, blue line), and grassland (green line). However, because the wavelengths in the antenna' s operating band are very long, actual testing is inevitably affected by the surrounding environment. For example, nearby mountains cause reflections, and the ground itself is a poor conductor with variable permittivity and conductivity. Consequently, test results may contain significant errors and cannot fully reflect the antenna' s performance in actual applications.

[Figure 9: see original paper] Simulation and measured S11 in different environments

[Figure 10: see original paper] Comparison of antenna and equivalent circuit impedance

Comparison of antenna and equivalent circuit impedance

In this study, our primary focus is the role of the non-Foster circuit in improving antenna performance. Therefore, we decided to test the antenna' s equivalent circuit loaded with the non-Foster circuit. However, this approach presents challenges. Low-order circuits cannot completely fit the antenna impedance, while high-order circuits are complex and introduce losses and parasitic effects. After comprehensive consideration, we adopted a segmented frequency testing approach: four equivalent circuits were fabricated to fit the antenna impedance at four frequency points. This method ensures reasonable accuracy. We selected frequency points at 4 MHz, 6 MHz, 8 MHz, and 9.5 MHz and created their equivalent circuits. Impedance measurements were performed using an impedance analyzer, with results shown in [Figure 10: see original paper].

The impedance before and after non-Foster improvement is shown in [Figure 11: see original paper]. The measured results basically agree with simulations, demonstrating that loading the non-Foster circuit improves the impedance of the electrically small butterfly membrane antenna and preliminarily confirming the feasibility of the proposed scheme.

[Figure 11: see original paper] Measured comparison diagram

Measured comparison

Below 10 MHz, sky background noise is extremely high, with sky temperatures on the order of hundreds of thousands to millions of Kelvin. For example, at 10 MHz the sky temperature is approximately 200,000 K, corresponding to a noise power density of about -140 dBm/Hz, which is comparable to or higher than the electronic noise of observation equipment [15]. Although non-Foster matching circuits increase system noise, their impact is relatively small. For accurate measurement, we used an Agilent N9020A spectrum analyzer with low noise power density to measure the noise spectrum with the non-Foster circuit off and on. The total measured noise values at V = 0 V and 12 V include both non-Foster circuit noise and the spectrum analyzer noise floor. The additional noise from the non-Foster matching circuit is the difference between measurements with the circuit on and off [16][17]. The noise spectrum test results are shown in [Figure 12: see original paper]. Compared with sky noise in this band, the overall circuit noise power density is relatively low and meets observation requirements. Additionally, the noise level is lower than that reported for some non-Foster circuits in other literature [17][16][17].

[Figure 12: see original paper] Noise power density measurement

4 Conclusion

Low-frequency radio astronomy below 10 MHz represents one of the few electromagnetic spectrum windows that have not been thoroughly explored and holds tremendous potential for scientific discovery. With physical length constraints on antennas, improving reception efficiency in this band is a highly worthwhile research problem. This paper proposes a design scheme for an electrically small butterfly membrane antenna loaded with a non-Foster matching circuit for low-frequency lunar radio observations, and presents simulation, fabrication, and measurement results. The results demonstrate that loading the non-Foster matching circuit can substantially improve antenna reactance, enabling good impedance characteristics even with electrically small dimensions, while maintaining circuit noise at acceptable levels. These results validate the feasibility of the proposed design scheme.

In future work, we will introduce transformer-based impedance transformation circuits to further improve impedance matching, investigate overall circuit stability, use simpler and more stable operational amplifiers to construct non-Foster circuits, and employ the same material as the antenna for the circuit substrate to attempt integrated antenna-circuit design. This will increase overall integration and provide technical reserves for future low-frequency antenna and matching network solutions in lunar radio astronomy arrays.

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