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An Active VHF and UHF Electrically Small Horn Antenna Using non-Foster Matching Circuit

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Abstract: In this article, an active electrically small Horn antenna for very high frequency (VHF) and ultra-high frequency (UHF) frequencies is presented. The proposed horn antenna has a height of 5 cm and a diameter of 4.28 cm which can cover 6-12 GHz without a special active circuit with the VSWR of less than 2. A non-Foster Active Adaptation Circuit is used to reduce the antenna input frequency from 164 MHz to 880 MHz. Good matching is visible between the simulation results and the measurement of the antenna reflection coefficient with the active matching circuit. The proposed structure has more than 137 % bandwidth. With the proposed active antenna, the problem of non-portability of VHF and UHF Horn antenna antennas has been solved. Finally, by analyzing the time domain, the stability of the circuit is examined, and the results of the stability test show that the system, including the antenna and the circuit, is stable. The antenna and the matching circuits are simulated by CST microwave studio and advanced design system, respectively.

Keywords: non-Foster, Dual-Ridged Horn Antenna, VHF, UHF, Small Antenna.

1 Introduction

SMALL antennas are very important in communication systems for reducing the size of the system where the antenna size at low frequency is a great challenge for researchers [1-2]. The use of electrically small antennas is not only limited to the communication system but also military work in the very high frequency (VHF) Band [3] and the high frequency (HF) Band [4]. So, recently various microstrip antennas have been developed for this goal [5-6]. For example, metamaterial such as composite right-hand/left-hand [7] and Electromagnetic Bandgap [8] techniques have been noticed for reducing the antenna size but these methods have many limitations such as narrow bandwidth which cannot be used for every kind of application [9].

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The Horn antenna has many applications in satellites transmitter and receiver [10], radars such as direction-finding systems [11], feed of the reflector antenna [12], and electromagnetic compatibility measurement systems and material sensing [13] and Ground penetrate Radar (GPR) [14-15]. Impedance matching of the electrically small horn antenna is very challenging due to the input resistance and high reactance [16], which makes it very difficult to adapt a small electric antenna to the source. To solve this problem, passive and active matching circuits are used for monopole and Ultra-wideband antennas [17-18].

Passive adaptation circuits include positive inductors and capacitors, and their reactance increases with increasing frequency. They also have a small bandwidth because they reduce the reactance value to zero at a certain frequency [19-20]. It is almost impossible to obtain wide bandwidths using passive circuits because there must be a compromise between the bandwidth and the minimum return coefficient (Γ_m) obtained from inactive networks [21].

Non-foster's active circuits include negative inductors and capacitors combined in series and parallel. The non-foster adjustment circuit reduces the antenna input reactance to zero in a wider frequency range. A non-foster circuit is a two-port active circuit that has two structures in the form of a negative impedance converter (NIC) [22] or a negative impedance inverter [21] that converts a passive element to a non-foster element [24-25]. However, the negative gain of the antenna with a non-foster circuit is a challenge, for example, the printed inverted F antenna (PIFA) antenna has been developed with a NIC circuit for 100-500 MHz with the gain of -20 dBi [26].

In this paper, an active small electric horn antenna is designed for frequencies from 164 MHz to 880 MHz (more than 137% bandwidth). Typically, the non-foster technique has been used before this for a narrowband antenna with an omnidirectional pattern while in this study we developed this technique for an ultra-wideband antenna (horn antenna) with a semi-directive pattern. For this aim, we suggest a conical dual ridge antenna which is modified for 6-18 GHz with the non-foster circuit. To implement the impedance matching, a stable open circuit negative impedance converter (OCS NIC) is used and connected in series to the antenna. The advantages of the proposed structure include 1) a physical size 40 times smaller than a 2-meter unipolar antenna designed for these frequencies, 2) Portability and lightness, and 3) Wide bandwidth.

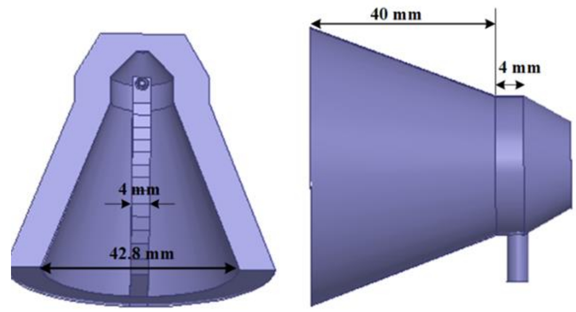
2 Electrically Small Horn Antenna Structure

A dual ridge conical Horn antenna which can provide UWB characteristics for 6-18 GHz [27] is used in this work. Two side views of the prototyped horn antenna are depicted in Fig.1 (a) and the fabricated antenna is presented in Fig.1 (b). The horn antenna consists of three parts: a circular waveguide, a conical cavity back, and an open aperture [27]. The radius of the aperture and total length of the horn antenna are 21.4 mm and 50 mm, respectively. The width of the ridge inside the circular waveguide is 4 mm and the ridge height is assumed 6.67 mm. The 50Ω SMA connector is implemented for exciting the antenna and is pinpointed in the conical cavity back part as shown in Fig.1. The radius of the chow sphere [28], the sphere containing the horn antenna, is 32.9 mm. This antenna at frequencies smaller than 720 MHz can be assumed as an electrically small antenna by considering the $ka < 0.5$ ratios, in which $k = 2\pi/\lambda_0$, λ_0 is the free space wavelength, and "a" is the radius of the chu's sphere.

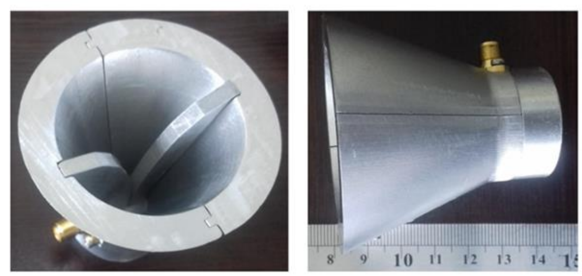
In fact, the small antenna is a comparative term and the size of an antenna can be defined by its physical size relative to the surrounding components. An antenna is considered small when the ratio is $Ka < 1$ for planar antennas and the ratio is $Ka < 0.5$ for non-planar antennas based on Wheeler-Chu-McLean formula as described by Eq. (1) [29].

$$Q = \eta_e \left(\frac{1}{(Ka)^3} + \frac{1}{Ka}\right) \approx \frac{\eta_e}{(Ka)^3} \ll 1 \qquad (1)$$

So, the proposed antenna with non-foster circuit can be supposed as an electrically small antenna for VHF and UHF applications. This antenna is simulated with CST microwave studio by Time-domain method and the VSWR of the antenna is checked by a network analyzer (HP8720c).



(a)



(b)

Fig. 1 Small electrically horn antenna (a) two side views of the antenna with dimensions (b) fabricated antenna.

3 Design of non-Foster Adaptation Circuit for Horn Antenna

To design a suitable a non-foster circuit for the proposed antenna, first, the input impedance of the antenna has been obtained. According to it, the amount of reactance generated by the non-foster circuit should be selected. Here, to reduce the reactance of the antenna at lower frequencies, a floating negative impedance circuit (NIC) as an open circuit (Floating OCS), based on cross-connecting two-transistors, is used based on previous basic theory on NIC circuit, that was introduced originally by Linvill [30]. The Advance Design System (ADS) software is used to simulate this NIC circuit. The schematic of the proposed non-foster circuit is shown in Fig. 2. The two transistors are biased as a common emitter and the LL inductor is located between the two transistors' bases [16].

In this circuit, a negative inductor is created to reduce the reactance of the horn antenna using two low-noise transistors NPN BJT (BFR93a) which is suitable for VHF and UHF circuits [31-32]. The two capacitors are located at the input and output of the circuit as a blocking capacitor for the DC block. In addition, a T-circuit is added for bias in the DC power supply section to the circuit to supply the currents of the transistor collector from the voltage source.

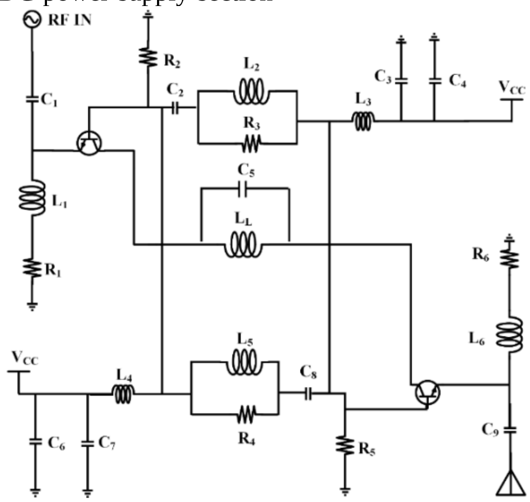


Fig. 2 Schematic of the stable non-foster matching circuit with antenna.

Using this structure, the DC and RF signals are separated. Then other elements are added to the non-foster circuit for bias and stabilization. The circuit is powered by two 8V power supplies for the best performance for low noise and more closely matched. The values of the elements are given in Table 1. The imaginary and real part of the input impedance of the horn antenna and non-foster circuits is presented in Fig.3 (a) to (d) in the range of 0.1 to 0.9 GHz, which shows the non-foster circuit provides stability and impedance matching to 50 Ω.

Different steps of designing a non-foster circuit for impedance matching the electrically small antenna are shown in a flowchart in Fig.4.

4 Antenna Simulation and Measurement Results with NIC Circuit

The two-port NIC circuit is printed on the FR-4 substrate as the low-cost substrate with a thickness of 1.6 mm and a permittivity of 4.6. The connection between the top and bottom layer of the PCB is made by metalized via holes. To make the simulation results more accurate, the parasitic effects of components such as packaging and self-resonance must be considered in the simulation, so the library of RF components for CoilCraft and Murata companies are used in this work [33-34].

The S-Parameter file for measuring the BFR93a transistor is implemented [35]. The antenna is also connected to the circuit output as an S1P file. Two ADS and CST software are used to simulate and analyze the entire antenna wave along with the NIC circuit. In the fabrication, the trimmer capacitor and potentiometer are utilized to optimize the results (due to the tolerance of the compressed elements). The NIC circuit is sensitive to changes in the values of the compressed elements and the associated additional noise.

In Fig. 5, the non-foster circuit is connected in series to the conical Horn antenna by a coaxial cable. The length of the coaxial cable is 6 cm. The red wire is connected to the voltage source and the black wire to the ground.

The reflection coefficient of the proposed dual-ridged conical horn antenna is presented for simulation and experimental in Fig.6 (a). It can be seen that the antenna has a wide bandwidth which covers 6-18 GHz with the reflection coefficient of less than -10dB and there is a good impedance matching between simulation and experimental results. The reflection coefficient of the modified antenna with the NIC circuit is shown in Fig. 6 (b). Measurement results show that the antenna covers from 164 to 880 MHz with a reflection coefficient of less than -10dB which makes it suitable for direction-finding applications in the VHF and UHF bands. There is a good correlation between the simulation and measurement results.

The measured radiation patterns of the horn antenna with the non-foster matching circuit are shown on two the E-plane and H-plane plates at two frequencies of 300 MHz and 600 MHz in Fig.7 (a) to (d) whereas the solid and dashed lines relate to co-polarization and cross-polarization, respectively. The antenna shows an omnidirectional pattern for the E-plane and a directive for the H-plane. Here, the presence of the wires and NIC board can be effective in the measurement of radiation patterns.

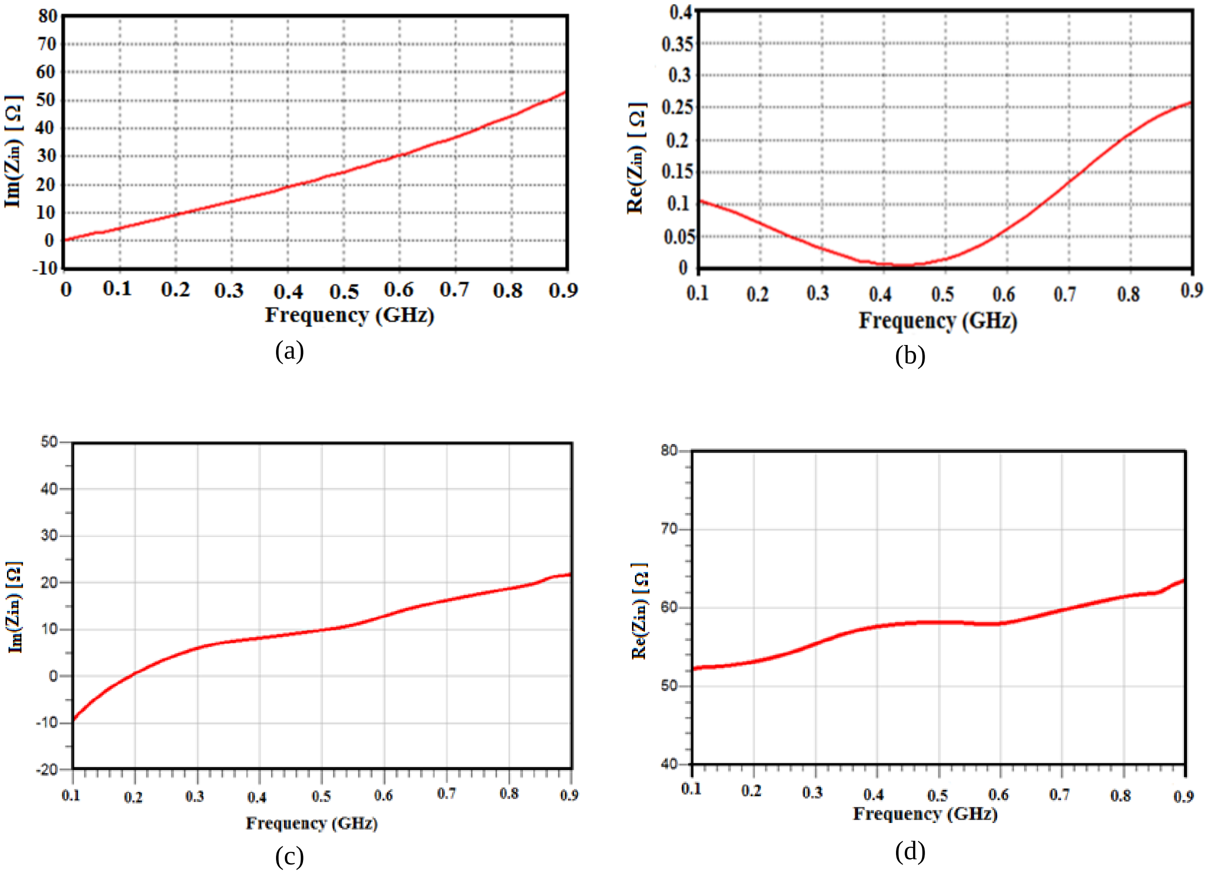


Fig. 3 (a) The imaginary part and (b) the real part of the input impedance of the horn antenna (c) the imaginary part and (d) the real part of the input impedance of the non-foster circuit.

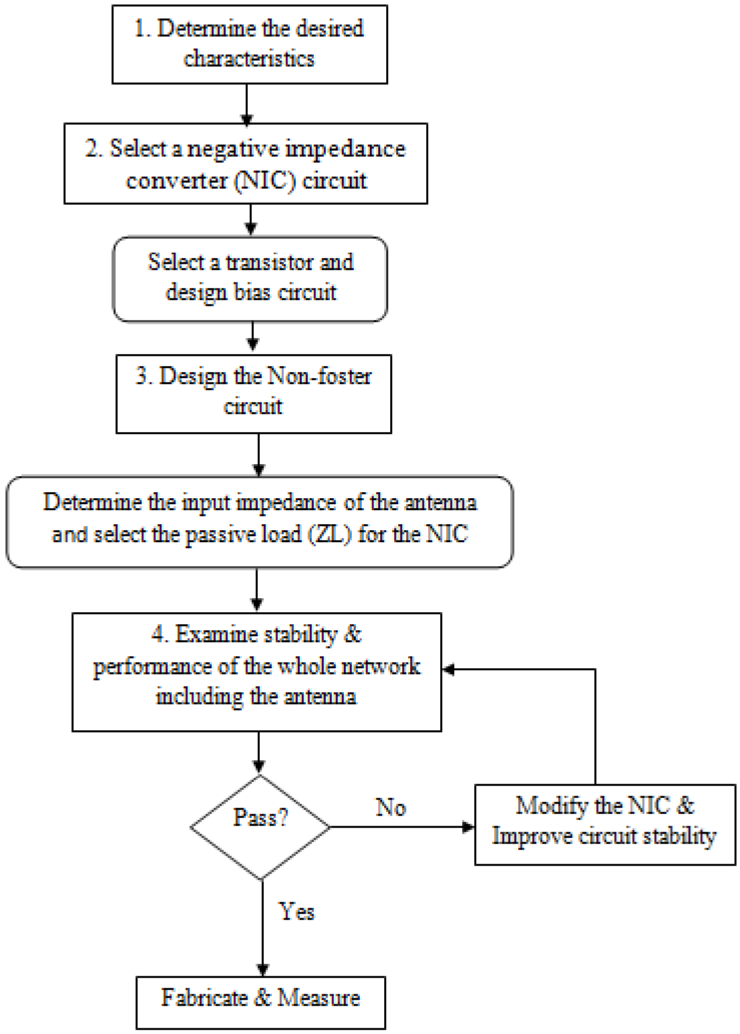


Fig. 4 The flowchart of different steps to designing a non-foster circuit for impedance matching of the antenna.

Table 1 Values of elements and their application in the proposed circuit.

Element	Value	Element	Value
R_3, R_4	10 Ω	C_1, C_9	220 PF
R_1, R_6	10 Ω	C_4, C_6	10 PF
R_2, R_5	18 Ω	C_7, C_3	100 PF
C_5	10 pF	L_1, L_6	1.8 nH
L_L	8.2 nH	L_2, L_5	1.8 nH
C_2, C_8	10 PF	L_3, L_4	100 nH

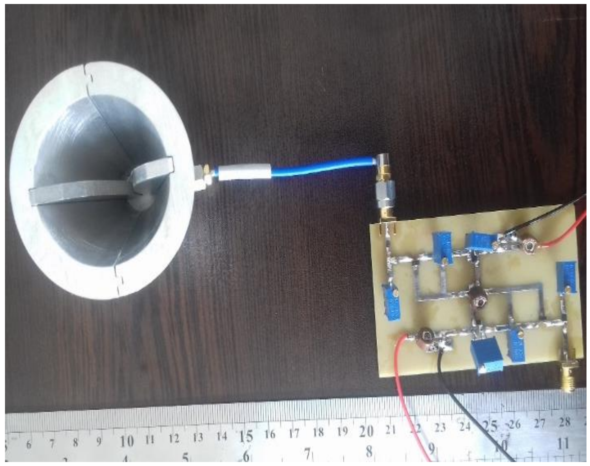
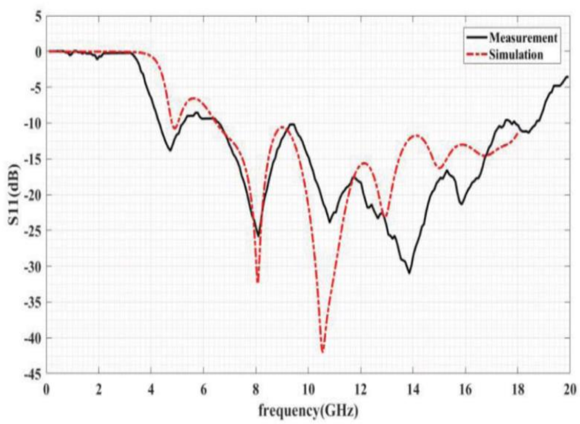
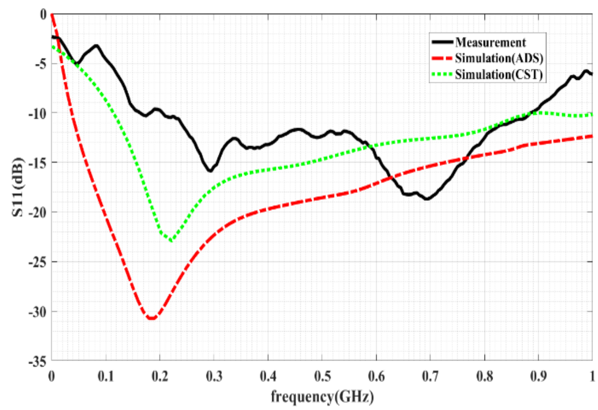


Fig. 5 The fabricated NIC circuit has been connected in series to the horn antenna.



(a)



(b)

Fig.6 S_{11} of the simulation and measurement of the horn antenna (a) without a non-foster matching circuit and (b) with a non-faster matching circuit.

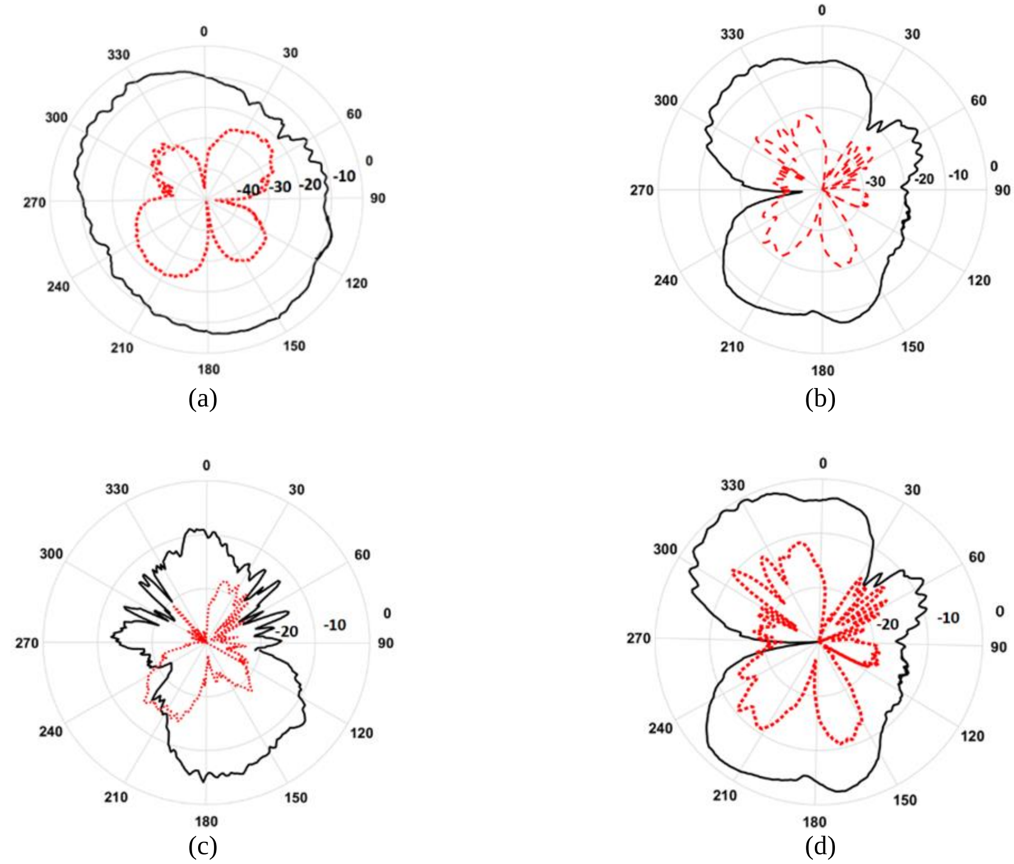


Fig. 7 The radiation patterns of the horn antenna with the non-foster matching circuit (a) E-plane and (b) H-plane at 300 MHz (c) E-plane and (d) H-plane at 600 MHz (the solid line for co-polarization and dash line for cross polarization).

5 Check the Stability of the non-Foster Matching Circuit with the Antenna

Due to the positive feedback, non-foster circuits are typically unstable. Therefore, it is necessary to check the stability of the whole system, including the antenna and the non-foster circuit. The time-domain analysis method has been used to investigate the stability [36-37]. For this goal at first, a pulse must be applied to the circuit and the convergence of the voltage signal at the input and output at the sensitive points of the circuit must be checked. Here a square pulse with a limited width is applied to the input of the circuit and the voltage at the output (between the circuit and the antenna) and a sensitive point of the circuit are investigated. As can be seen in Fig.8 (a) and (b), the voltage signal is converged to a fixed number, which means that the whole system is stable.

Two methods of Roulette and time-domain analysis have been used to investigate [26, 36]. In the stability study, the circuit must be connected to the antenna and then the stability test must be performed. The most common test for RF circuit stability is the Roulette test. In the Roulette stability test method, $K > 1$ and $|\Delta| < 1$ and also $1 < \mu$ until the network is stable with the antenna without conditions. Fig. 8 (c), (d), and (e) show the value of these three parameters in terms of frequency. It is observed that in all three parameters, the conditions of circuit stability are established.

6 Comparison with Previous Study on non-Foster Antenna

Recently, various types of antennas with non-foster circuits have been developed for VHF and UHF applications. The proposed antenna type, frequency, bandwidth, gain, and efficiency are compared with other studies in Table 2. The proposed antenna shows 137% bandwidth which is typically more than most of the studied models and only in [16] the antenna with a higher bandwidth of about 190 % is reported. The negative gain and low efficiency are conventional in this type of antenna because this type of antenna is typically used for receiving the electromagnetic signal in the receiver including direction-finding systems. The Proposed antenna has a directional pattern in the H-plane with a null and omnidirectional pattern for the E-plane. So, this antenna can be used for direction finding in the VHF and UHF based on its E-plane.

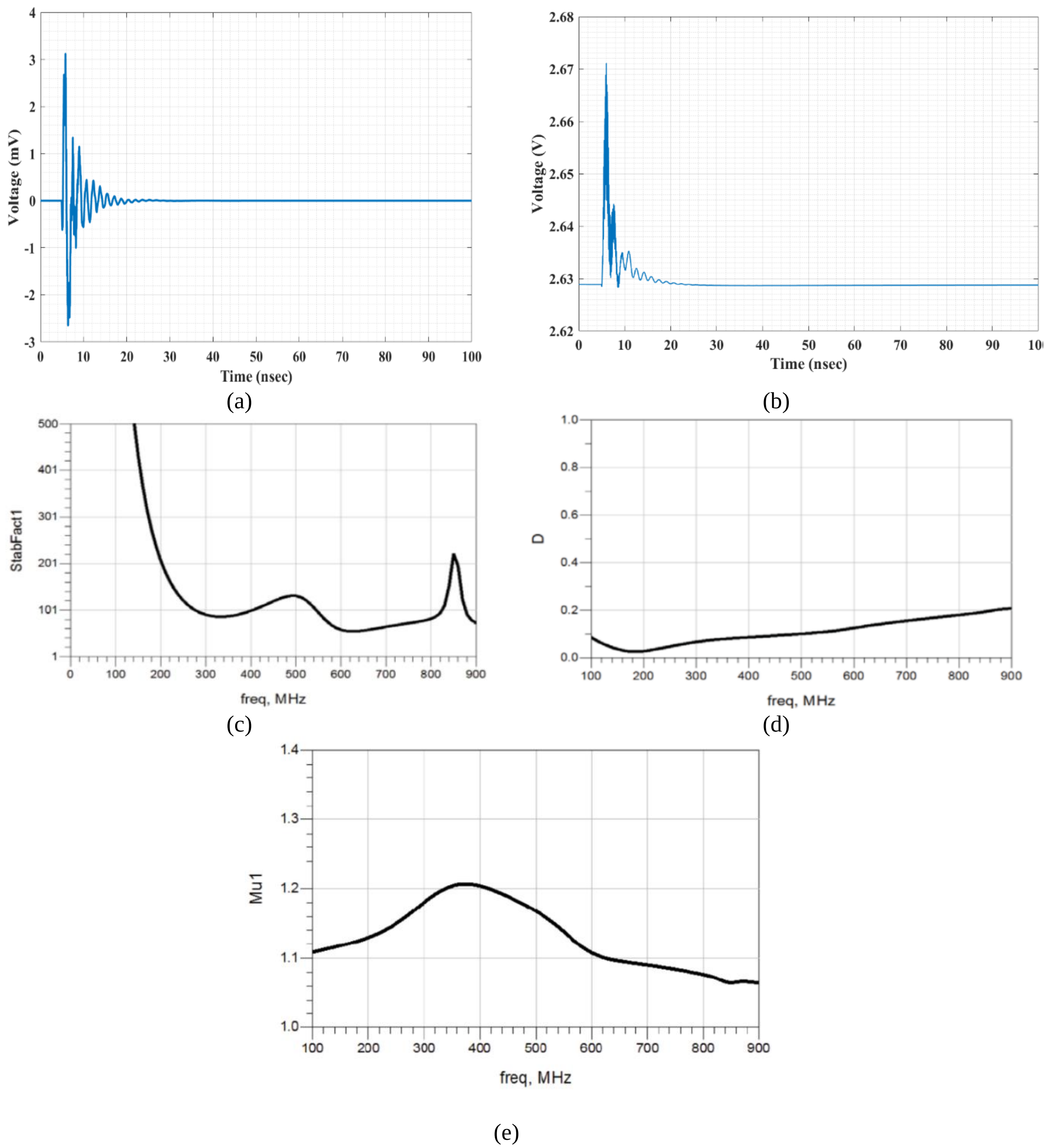


Fig. 8 Stability factors (a) Voltage signal amplitude at circuit’s output (between circuit and antenna) (b) Voltage signal amplitude at a critical point of the circuit (c) Stability factor of K (d) Stability factor of |Δ| (e) stability factor of μ.

7 Conclusion

The non-foster technique can be used to design the compact antenna as an electrically small antenna by considering the ka <0.5 ratios for portable applications such as direction-finding. As shown in this paper, the conical horn antenna can be interesting for this goal which covers a wide bandwidth between 160 to 880 MHz. This antenna has more bandwidth in comparison with some models including monopole antennas [26]. The stability diagrams prove that this antenna and circuit have appropriate stability for both Roulette and time-domain analysis. The antenna shows an omnidirectional pattern for the E-plane and a directive for the H-plane.

Table 2 Compares the proposed antenna with some previous studies.

	Antenna Type	Bandwidth (S_{11}<-10 dB)	Gain (dB)	Max Efficiency (%)
Proposed antenna	Horn Antenna	164 to 880 MHz (137%)	-20 to 4 dB	80 %
Ref [16]	Horn Antenna	100 to 2400 MHz (190%)	8.9 dB	------
Ref [38]	dipole antenna	280-320 MHz (15%)	2.21 dB	95 %
Ref [39]	PIFA	800 to 2400 MHz (100%)	-8 to 3.5 dBi	80 %
Ref [32]	PIFA	800 to 1400 MHz (55%)	-10 to -3 dBi	25 %
Ref [26]	PIFA	120 to 520 MHZ (125%)	-40 to -5 dB	------------

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