A Non-Foster UWB Electrically Small Planar Monople Antenna (ESPMA)

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Abstract. Electrically small antennas (ESAs) may be employed instead of full-size antennas in a limited space for many communication networks such as the very high-frequency (VHF) band applications and ultra high-frequency (UHF) band applications. However, ESAs cannot simultaneously achieve high gain and broadband by passive matching due to the gain-bandwidth theory. This paper presents a ultra wide-band (UWB) transmit electrically small planar monople antenna (ESPMA) with a non-foster impedance matching to bypass the restriction of the gain-bandwidth theory. The proposed antenna is composed of a planar monople antenna with a height of 10 cm in profile and a non-Foster circuit. The plane monople antenna is chosen because of its better impedance performance than a cylindrical monople. The proposed antenna can operate in the band range of 80 MHz - 500 MHz (145%, VSWR<2.5) much greater than the maximum bandwidth of 0.285% in the theory of matching with the conventional passive circuit. The transmission efficiency of the antenna is improved by as much as 31 dB compared with the same antenna without the proposed matching network. Besides, the stability of the proposed matching network is remained within the operating band.

1. Introduction
Electrically small antennas (ESAs) are required instead of the full-size antennas due to their smaller dimensions, especially the very high-frequency (VHF) band (30–300MHz) and ultra high-frequency (UHF) band (300-3000 MHz) [1-4]. However, for ESAs, the very high radiation quality factor (Q) is presented due to their very small radiation resistance and large reactance [5-8]. Therefore, it is challenging for ESAs to obtain the broadband and high transmission efficiency. Conventional passive matching networks composed of the Foster circuits can achieve the broadband with the poor performance of the transmission efficiency [9-11]. Thus, for transmit antennas, a larger transmitter and prime power source are required to provide desired output power. For receive antenna, low transmission efficiency means lower sensitivity, i.e., poor signal-to-noise ratio.

An non-Foster matching circuit can achieve the broadband without the sacrifice of the gain for bypassing the gain-bandwidth restrictions by canceling out the reactance of the ESA over a wide frequency band. This technology has been widely employed in receiving ESA systems[12-14]. Paper [12] proposed the earliest non-Foster matching circuit used for receiving ESA antennas. In this paper, a negative capacitance controlled by a voltage feedback loop was achieved by the multistage transistor-based circuit, while the negative capacitance was realized using operational amplifiers in [13]. The design presented in [14] did not achieve an optimum noise figure due to the effects of the noise temperature. Furthermore, few studies have been published for transmit applications[4,15]. In [15], non-Foster circuit with a constant resistance terminal achieved up to 20 dB more transducer...
power gain than any passive design over the band of 15 MHz - 30 MHz. In [4], a wideband transmit ESA matched with a non-Foster network was presented. The antenna operated in the frequency band of 26 MHz-89 MHz with a slender cylindrical monopole structure (32cm in profile).

In this paper, we present a novel transmit ultra-wideband electrically small planar monopole antenna (ESPMA) matching with non-Foster matching network. The proposed antenna is composed of a planar monopole antenna with a lower height of 10cm in profile and a non-Foster circuit which consists of a isolated circuit, a negative impedance converter (for imaginary-part matching), and a multiple orders passive L-matching network (for real-part matching). A planar monopole structure is designed instead of the slender cylindrical structure because of the relatively flat impedance characteristics and low profile. The proposed antenna can operate in the band range of 80 MHz - 500 MHz (145%, VSWR<2.5) greater than the maximum bandwidth of 0.285% in theory of matching with the conventional passive matching. The transmission efficiency of the antenna is improved by 31dB compared with the same antenna without the proposed matching network. Besides, the stability of the proposed matching network can be remained within the operating band. The proposed antenna can be used for many applications in a limited space.

2. The structure of ESPMA

2.1. The planar monopole antenna of ESPMA

The radiator of the planar monopole antenna fed by SMA connector is a copper rectangle plane (height: 10cm, width: 8cm) etched on the substrate whose thickness is 1cm as shown in Fig. 1(a). The material of the substrate is FR4 ($\varepsilon=4.4, \tan\delta=0.02$). The dimensions of the copper ground are $10cm \times 10cm$ for miniaturization. The copper rectangle plane of the radiator is placed vertically over the ground with separation of 1mm. Fig. 1(b) shows a cylindrical monopole antenna for comparison. The cylindrical monopole antenna has the same diameter as the antenna proposed in [4]. The height of the copper cylinder and the size of the copper ground are the same as the planar monopole. The simulations were designed by ANSYS Electronics Desktop.

![Figure 1. The structures of (a) the planar monopole antenna and (b) the cylindrical monopole.](image)

Fig. 2 depicts the input impedance of the planar monopole compared with that of the cylindrical monopole. Fig. 2(a) shows the input resistance, while Fig. 2(b) depicts the input reactance. It can be observed that more flat resistance and lower reactance are obtained for the planar monopole compared with those of the cylindrical monopole.
Figure 2. The input impedance of the planar monople antenna compared with that of the cylindrical monople antenna: (a) input resistance; (b) input reactance.

Fig. 3 depicts the peak gain of the planar monople antenna. Due to low radiation resistance shown in Fig. 2 and the mismatching in the port of the planar monople antenna, the peak gain of -37.8 dBi - -5.2 dBi is generated over the band of 80 MHz - 500 MHz. Ideally, assuming that the planar monople antenna is conventional lossless matched over the frequency band of 80 MHz - 500 MHz, the upper bound of the peak gain of the ideal matched planar monople antenna is -12.9 dBi - 2.3 dBi as shown in Fig. 3. Therefore, the gain of planar monople antenna operated in this frequency band is low.

Figure 3. The peak gain of the planar monople antenna compared with that of the ideal matched planar antenna

Furthermore, in theory, the maximum available bandwidth of the planar monople antenna passive matched with conventional passive circuits can be calculated as [4]

$$B = \frac{VSWR - 1}{\eta Q \sqrt{VSWR}}$$  \hspace{1cm} (1)

$$Q = \frac{1}{ka} + \frac{1}{(ka)^3}$$  \hspace{1cm} (2)

Where $Q$ is the quality factor. $k$ denotes the wave-number ($k=2\pi/\lambda$), $a$ denotes the radius of the minimum size sphere that encloses the antenna, $VSWR$ denotes the voltage standing wave ratio, $B$ is the upper bound of the matched $VSWR$ fractional bandwidth, and $\eta$ is the radiation efficiency. For the planar monople antenna, using $a=0.087 m$ and $k=2\pi/\lambda=1.67$ at 80 MHz results in $Q=333$. Assuming that $\eta=100\%$ and $VSWR=2.5$, the upper bound of the bandwidth is about 0.285\%. To achieve UWB for the
planar monople antenna with the high gain, a matching network composed of an isolated circuit, a negative impedance converter and a multiple orders L-matching network is employed.

2.2. The matching network of ESPMA

The matching network of ESPMA is shown in Fig. 4. The matching network consists of a isolated circuit, a negative impedance converter (NIC, for imaginary part matching) and a multiple orders L-matching network (for real-part matching). The isolated circuit is a single-stage common-base amplifier to provide a power gain and a high isolation between the planar monople antenna and the negative impedance converter. The high isolation can alleviate the system stability problem since it decrease the closed-loop feedback gain of the system[12]. The isolated circuit is composed of a transistor (2SC3583, $\beta=110$, $V_{CEO}=10V$), a bias circuit (four resistors), RF chokes and dc blocks. Due to the requirements of providing gain and operating reliably, the transistor must operate in the the forward-active region of operation, and de operating point for the transistor is designed at $I_C=40mA$, $V_{CEO}=2.5V$. Therefore, four resistors of the bias circuit can be determined as shown in Table 1. The RF choke in the proposed isolated circuit is composed of two cascade inductors ($L_{RF}=2.7\mu H$) for required large impedance. Capacitors $C_{DC}=47nF$ are employed as dc blocks. The circuit was mounted on an FR4 substrate.

![Figure 4. The matching network of ESPMA. It consists of a isolated circuit, a negative impedance converter (NIC), and a L-matching network.](image)

| Comment | Model/value | Comment value |
|---------|-------------|---------------|
| transistor | NE68133 | $L_8=7.5nH$ |
| $L_{RF}$ | 2.7$\mu H$ | $L_9=1.2nH$ |
| $C_{DC}$ | 47pF | $L_{10}=1.5nH$ |
| $C_{DC1}$ | 10pF | $L_{11}=1nH$ |
| $R_e$ | 237$\Omega$ | $L_{load}=16nH$ |
| $R_b1$ | 196$\Omega$ | $C_1=7.5pF$ |
| $R_{b2}$ | 1.1k$\Omega$ | $C_2=16pF$ |
| $R_{b3}$ | 1.33k$\Omega$ | $C_3=20pF$ |
| $V_{CC}$ | 20V | $C_4=1pF$ |
| $L_1$ | 20nH | $C_5=2pF$ |
| $L_2$ | 19nH | $C_6=12pF$ |
The S-parameter of the isolated circuit is shown in Fig. 5. Observe that the isolated circuit provide a $S_{21}$ of around 5dB and a $S_{12}$ below -45 dB over the frequency band of 80MHz-500MHz. Also, the voltage gain ($|V_{OUT}|/|V_{IN}|$) of the isolated circuit is greater than 21 dB as shown in Fig. 6. Therefore, a voltage gain and high isolation ($S_{12}$) can be realized by employing the isolated circuit.

![Figure 5. The S-parameters of the isolated circuit](image1)

![Figure 6. The voltage gain ($|V_{OUT}|/|V_{IN}|$) of the isolated circuit](image2)

To matching input reactance of the planar monpole antenna and the isolated circuit, a negative impedance converter (NIC) is designed. The structure of the NIC is based on a Linvill’s floating NIC [12] that consists of two transistors, bias circuits, RF chokes and dc blocks as shown in Fig. 4. the values of these comments can be observed in Table 1. the NIC is a symmetrical circuit, and the circuit layout is also symmetrical. Fig. 7 depicts the input reactance of the NIC terminated with 50Ω. It can be observed that the negative reactance to frequency slope can be realized, which is in agreement with the theory of non-Foster circuit.
Fig. 7. The input reactance of the NIC.

Fig. 8 depicts the input impedance of the circuit composed of the planar circuit, the isolated circuit and the NIC. The input reactance of the input impedance is around $0\,\Omega$ over the frequency band of 80MHz-500MHz. The input resistance of the input impedance is around $11\,\Omega$ over the required band. To match real-part of the input impedance, a multiple orders L-matching network is employed. The orders of the network are denoted $N$. More orders the network is, wider frequency band the network can be achieved. Therefore, $N$ is determined to be equal with 11 after compromising circuit complexity and bandwidth.

Fig. 8. The input impedance of the circuit composed of the planar monopole antenna, the isolated circuit (isolated) and the negative impedance converter (NIC).

3. Performance of ESPMA
The reflection coefficient ($S_{11}$) of ESPMA is shown in Fig. 9 compared with that of the planar monopole antenna operating alone. The $S_{11}$ of ESPMA is below -7.4 dB ($VSWR=2.5$) over the frequency band of 80MHz-500MHz, while the $S_{11}$ of the planar monopole antenna operating alone is around 0dB, which means the planar monopole antenna is almost completely mismatched. Therefore, the planar monopole antenna can achieve required matching by introducing the matching circuit composed of the isolated circuit, the NIC and the multiple L-matching circuit.
The transmission property of ESPMA is also researched. The transmission coefficient (S21) of ESPMA is depicted in Fig. 10 compared with that of the planar monopole antenna in isolation. Besides, the improvement of S21 of ESPMA is also illustrated in Fig. 10 compared with the planar monopole antenna. The S21 of the planar monopole antenna is determined by the reflection coefficient because the summation of the square of them is one. The S21 of ESPMA is calculated by the same way. Please note that the values of S21 in dB scale are equal to those of the transducer power gain (transmission efficiency) in dB scale. It can be observed that ESPMA achieves 31dB improvement of S21, which means that the transmission efficiency of ESPMA is improved by as much as 31dB compared with the same antenna without the proposed matching network.

Finally, the stability of ESPMA is concerned due to active components in ESPMA. It is very critical that the stability of ESPMA is ensured to avoid spurious radiation from the antenna. To analyse the stability of ESPMA, stability factors $\mu$ and $\mu'$ are given by [16]

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}^*| + |S_{12}S_{21}|}$$

(3)
where '*' denotes complex conjugate. \( \Delta \) is calculated by
\[
\Delta = S_{11}S_{22} - S_{12}S_{21}
\]

The value of the stability factor \( \mu (\mu') \) gives the distance from the center of the Smith chart to the nearest unstable load (source) impedance values. If \( \mu>1 (\mu'>1) \), ESPMA is unconditionally stable. The stability factors of ESPMA are shown in Fig. 11. It can be observed that ESPMA is unconditionally stable over the frequency band of 80MHz-500MHz.

### 4. Conclusion
In the paper, a low profile, novel transmit electronically small planar monople (ESPMA) with non-Foster circuit has been designed. The antenna is composed of a planar monople antenna with the height of 10cm in profile and a non-Foster circuit. The non-Foster circuit consists of an isolated circuit, a negative impedance converter (NIC, for imaginary-part matching), and a multiple orders passive L-matching network (for real-part matching). A planar monople structure has been designed instead of the slender cylindrical structure because of the flat impedance characteristics. The proposed antenna can operate in the frequency band of 80 MHz -500MHz (145%, VSWR<2.5) much greater than maximum bandwidth of 0.285% in theory of matching with the conventional passive matching. The transmission efficiency of the antenna has been improved by 31dB compared with the same antenna without the proposed matching network. Besides, the unconditionally stability of the proposed antenna can be remained within the operating band.

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