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Non-Foster Matched Antennas for High-Power Applications

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Abstract—A non-Foster matching network has been designed for a small cylindrical slot antenna, and its broadband matching capability has been examined at varying signal power levels. It has been observed that the non-Foster circuit (NFC) impedance changes considerably as the signal power increases, thus reducing its matching capability as well as introducing stability problems. To analyze its true advantage in transmit applications, the third-order intermodulation output intercept point (OIP3) and the gain-bandwidth product of the non-Foster matched antenna have been compared with the unmatched antenna, when both are attached to the same power amplifier. Simulations show that the unmatched antenna has a higher OIP3 and gain-bandwidth product, despite being more poorly matched. Although the OIP3 can be slightly improved by increasing the bias current of the NFC, improved linearization techniques should be studied to offset distortion effects in NFCs.

Index Terms—Active antenna matching, negative impedance convertor, non-Foster circuit (NFC), nonlinear distortion, small antennas.

I. INTRODUCTION

NON-FOSTER circuits (NFCs) are powerful tools to overcome bandwidth and performance limitations of passive antennas [1], [2] and metamater ial structures. However, they are active circuits with nonlinear transistors, which can introduce undesirable effects at high signal power levels. An NFC with very low parasitics and high quality factors can introduce nonlinearity issues at signal power levels as low as $-25$ dBm [3]. To determine distortion effects or nonlinear characteristics of NFCs, high-power measurements and simulations have been performed for a non-Foster matched cylindrical slot antenna [4]. It has been observed that the NFC impedance changes considerably as the signal power increases, thus reducing its matching capability as well as introducing stability problems for signal power levels above $-15$ dBm. Two-tone inputs of varying signal power levels were then given to the NFC matched antenna, and the reflected mixing products were measured to analyze stability issues. The alternative to a non-Foster matched antenna with a transmit power amplifier is an unmatched antenna with the same transmit power amplifier as shown in Fig. 1, to determine which system can deliver the highest gain-bandwidth product and third-order intermodulation output intercept point (OIP3). The gain of the two systems was compared for varying input signal power levels. The radiated OIP3 simulations were also performed for the two systems. Overall results show that for the particular NFC matched antenna under consideration, the unmatched antenna system has a better high-power performance in terms of gain and OIP3, despite being more poorly matched than the NFC matched antenna for low-power signal levels. However, on increasing the bias current in the NFC design, the OIP3 was found to improve for the NFC matched antenna. Further research needs to be done on optimum design techniques for high-power NFC matched antennas to guarantee minimal gain degradation along with improved stability and OIP3.

II. SMALL SIGNAL INPUT MATCH AND GAIN

A cylindrical slot antenna of diameter 16 cm, and height 20 cm with a resonant slot of width 3 mm was designed, as shown in Fig. 2(a). Since the antenna has a balanced mode of operation, a balun was used to convert the antenna’s balanced feed into a single ended feed. The input impedance of the antenna (with balun) was measured, and an equivalent $RLC$ network was developed to model the antenna’s impedance, as shown in Fig. 2(b). From Fig. 2(c), it can be
Fig. 2. (a) Cylindrical slot antenna with active matching network circuit. (b) Equivalent RLC network of the measured antenna impedance. (c) Measured antenna impedance compared with the equivalent RLC network impedance.

seen that the equivalent RLC network’s impedance matches the measured antenna impedance up to 500 MHz.

In order to provide a conjugate impedance match to this antenna at low frequencies, it is necessary to cancel the reactance of 103 nH || 9.7 pF [Fig. 2(b)], which contributes to the low frequency impedance of the antenna [Fig. 2(c)]. Therefore, we designed an ideal non-Foster matching network shown in Fig. 3(a), consisting of −98 nH || 2.2 pF that is attached in parallel to the antenna to cancel its reactance, along with providing an additional non-Foster reactance to the inductive transformer network that transforms the antenna’s radiation resistance toward a 50-Ω match. While broader bandwidths may be obtained by more complex non-Foster matching schemes, this network was designed with minimal non-Foster elements to ensure greater circuit stability. The simulated input match of this ideal non-Foster matched balun-fed antenna is shown in Fig. 3(c), along with the measured input match of the passive balun-fed antenna. A broadband input match improvement is observed at the low frequencies.

To implement the required non-Foster impedance, the cross-coupled transistor topology [5], [6] of the NFC was chosen, and the −L || −C circuit was implemented as a short circuit stable (SCS), single ended configuration. The entire matching network topology consisting of the NFC and inductive transformer was laid out on an FR-4 printed circuit board (PCB). A cosimulation technique was used wherein an electromagnetic simulation software, such as Ansys HFSS [7], was used to extract the layout parasitics and a circuit simulation software, such as Keysight ADS [8], was used to attach actual device models to the layout. The transistors used were Avago AT41511 bipolar junction transistors (BJTs). The circuit was optimized to have low loss in the matching bandwidth while providing the necessary reactance to cancel the reactance of the antenna. The circuit schematic of the NFC matched antenna (including the inductive transformer) along with the optimized values of the components is shown in Fig. 3(b). The NFC provides the negative admittance of the series elements R_load, L_load and C_load [Fig. 3(b)] to cancel the reactance of the antenna. The inductive transformer (Ind1 and Ind2) transforms the antenna’s resistance to 50 Ω. It should be noted that the values of the inductive transformer and the non-Foster impedance are slightly different from the ideal values shown in Fig. 3(a) owing to the addition of device and layout parasitics. The NFC

Fig. 3. (a) Ideal non-Foster matching network with inductive transformer designed for the measured antenna impedance. (b) Non-Foster matching circuit schematic. (c) |S11| of the ideal non-Foster matched antenna and NFC matched antenna compared to that of the passive antenna.
was designed to be stable with the inductive resistance transformer and the antenna; therefore, an accurate deembedded NFC measurement could not be obtained.

The entire matching network consisting of the NFC and inductive transformer was fabricated on an FR-4 PCB and attached to the antenna, as shown in Fig. 2(a). When the NFC bias was turned OFF, the inductive resistance transformer acted as a passive matching network and provided a measured $-6$ dB match from 157 to 177 MHz, as shown in Fig. 3(c). When the NFC bias was turned ON, we achieved an improved measured $-6$ dB matching bandwidth from 30 to 135 MHz. In Fig. 3(c), it is seen that $|S_{11}|$ is greater than 1 for some low frequencies. However, the NFC was found to be stable at all frequencies. The simulated and measured small signal input matching characteristics are very similar as seen in Fig. 3(c).

III. LARGE SIGNAL INPUT MATCH AND GAIN

A. Large Signal Input Match

Large signal S-parameter simulations were conducted for the NFC matched cylindrical slot antenna for various input signal power levels ranging from $-30$ to 5 dBm. From the simulation results [Fig. 4(a)], it can be observed that at small input power levels (less than $-25$ dBm), the matching bandwidth is the same as that seen in S-parameter small signal simulations. As the input power increases, the matching begins to degrade, both in terms of $S_{11}$ magnitude as well as matching bandwidth. Thus, the matching capability of the NFC becomes less pronounced as the input power increases. At input power levels greater than 5 dBm, the input match is as if the NFC bias were turned OFF [Fig. 3(c)].

These results were verified through measurements, as shown in Fig. 4(b). It can also been observed that at certain high input power levels, there are measured spikes in the reflection characteristics, corresponding to instabilities at these frequencies. The possible reasons for these instabilities will be discussed in Sections IV and V. Performing a smoothing operation on these curves gives similar results to the simulation curves. Thus, although harmonic balance simulations can predict most nonlinear effects, transient high power instability could not be accurately simulated.

B. Large Signal Gain

Large signal $S_{21}$ simulations were conducted after assigning the 50-Ω input in Fig. 3(b) as port 1 and the passive antenna as port 2, to provide the transducer gain in the transmit mode for different input power levels from $-30$ to 5 dBm (Fig. 5). The transducer gain thus calculated is the realized gain of the antenna, which includes the effect of input mismatch. It can be seen that transducer gain reduces considerably, as the input power is increased. This is partly due to the poor input match at high power levels, and also due to the nonideal NFC impedance at high power levels, as shown in Fig. 6. Fig. 6 shows the simulated one port impedance of the short circuit NFC ($-L \ || -C$) in Fig. 3(b) without including either the inductive transformer or the antenna connected to it. As input power increases, the reactance of the NFC deviates from its designed values and the resistive loss increases, leading to an input mismatch and a loss in gain. The high-power NFC impedance magnitude is seen to be much higher than the low-power impedance magnitude, and therefore, this does not

![Fig. 4](image_url)

![Fig. 5](image_url)
Fig. 6. Simulated NFC resistance and reactance for input power levels from $-30$ to $5$ dBm.

violate the SCS condition of the NFC. To further investigate the cause of instabilities, high-power two-tone measurements were performed.

IV. HARMONICS AND MIXING PRODUCTS AT HIGH POWER

Typically, a two-tone measurement in a nonlinear system yields harmonics of the two tones, along with the second-order and third-order mixing products, according to the following power series expansion for distortion [9], [10]:

$$V_{\text{out}} = a_1 V_{\text{in}} + a_2 V_{\text{in}}^2 + a_3 V_{\text{in}}^3 \ldots$$  

where $a_1$, $a_2$, and $a_3$ are the first-order, second-order and third-order coefficients of nonlinearity. Highly nonlinear systems have nonlinearity coefficients of the fourth order and higher, leading to a greater number of mixing products in the output.

In a radiating system, it is difficult to measure radiated mixing products generated by active circuits before the antenna. One reason is that the generated harmonics and mixing products are typically about $20$ dB or more below the power of the fundamental tones, and therefore, it becomes harder to measure low-power radiated mixing products. Another reason is that the antenna acts like a natural filter due to the frequency dependence of the gain, with the harmonics seeing much lower gain than the fundamental tones. Therefore, in order to capture most of the nonlinear harmonics and mixing products generated by the NFC attached to the antenna, a measurement setup similar to the passive intermodulation (PIM) test setup was devised to measure the reflected mixing products instead of the radiated mixing products, as shown in Fig. 7(a).

The large number of mixing products around the fundamental tones indicates the high nonlinearity of the NFC. This was confirmed on increasing the power of the input tones. When the input is a single tone of $99$ MHz at $0$ dBm [Fig. 8(a)], the reflected coupled power at the spectrum analyzer shows only the fundamental tone and the second harmonic. When a two-tone input is sent, with the addition of $100$ MHz at $0$ dBm,
the reflected power shows mixing products across a wide range of frequencies as shown in Fig. 8(b), instead of the typical triangular patterns centered around the fundamental tones and their harmonics. This could be due to the mixing products mixing amongst themselves due to the positive feedback within the NFC, generating new mixing products of various frequencies.

It should also be noted that at high power, the harmonic balance simulations cannot accurately predict measurement results unless a very large mixing order is enabled in the simulations (due to the positive feedback effect). Current resources did not enable us to perform simulations with the mixing order required to generate mixing products across the wide range of frequencies seen in the 0-dBm input measurements. However, nonlinear simulations closely match measurements for signal power levels under $-10$ dBm, and this allows us to calculate the extrapolated third-order output intercept point for the non-Foster matched antenna.

B. Simulated Two-Tone Radiated Distortion Products

Two-tone simulations were performed for the NFC matched antenna to analyze the power of the radiated fundamental tones versus the power of the radiated third-order intermodulation product. Two tones of $f_1 = 99$ MHz and $f_2 = 100$ MHz were sent to the input of the NFC matched antenna, and the radiated fundamental tones $f_1$ and $f_2$ were calculated, along with the lower IM3 product $2f_1 - f_2$ and the upper IM3 product $2f_2 - f_1$. Care must be taken to ensure that the power calculation takes into account the frequency-dependent impedance of the antenna by using the radiation resistance of the antenna at the respective fundamental tones and the IM3 frequencies. The simulated results are shown in Fig. 9.

A visual inspection of Fig. 9 shows that the extrapolated third-order intermodulation product intersects the fundamental tone at around $P_{in} = -16$ dBm. This gives the third-order intermodulation input intercept point (IIP3). The third-order intermodulation output intercept point (OIP3) is given by the output of the extrapolated linear fundamental power at the IIP3, which is equivalent to $-22$ dBm, as shown in Fig. 9. The reason for the OIP3 being lower in power than the IIP3 is that the NFC matched antenna has a transducer gain lower than 1 (the maximum transducer gain of an antenna, given by the ratio of the total radiated power to the input power, is 1 for an antenna with an ideal input match and efficiency). The OIP3 can also be calculated using the following equations:

$$\text{OIP3}_{\text{low}}(\text{dBm}) = P(f_1) + 0.5(P(f_2) - P(2f_1 - f_2))$$

$$\text{OIP3}_{\text{high}}(\text{dBm}) = P(f_2) + 0.5(P(f_1) - P(2f_2 - f_1)).$$

In the above equations, $P(f_1)$ is the output power of the lower fundamental tone (in dBm), $P(f_2)$ is the output power of the upper fundamental tone (in dBm), $P(2f_1 - f_2)$ is the output power of the lower IM3 product (in dBm), and $P(2f_2 - f_1)$ is the output power of the upper IM3 product (in dBm). $\text{OIP3}_{\text{low}}$ and $\text{OIP3}_{\text{high}}$ should be identical for a systems where the gain is invariant across the frequencies from $2f_1 - f_2$ to $2f_2 - f_1$. Due to the small gain variation of the NFC
matched antenna across these frequencies, the two values of OIP3 are not exactly the same, but have variations under 0.3 dBm. The simulations required for the power values in the OIP3 calculations must be performed at well below the compression point of the NFC matched antenna to guarantee accurate results.

The IIP3 can be calculated as

\[
IIP3_{\text{low}}(\text{dBm}) = OIP3_{\text{low}}(\text{dBm}) - \text{Gain}(\text{dB}).
\] (4)

The simulated IIP3 of −16 dBm is quite low compared with most high-power amplifiers. But more worrying is the presence of instabilities at power levels greater than −15 dBm.

V. REASON FOR HIGH POWER INSTABILITY

One of the reasons for high power instability could be the large number of mixing products generated across the bandwidth of operation due to positive feedback and self-mixing. This could manifest itself as “instability” in S11 measurements, as shown in Fig. 8(b).

Another reason could be observed from the IM3 products in Fig. 9. The IM3 starts to deviate from its linear curve and starts to dip at input power levels around −15 dBm. This could be explained by the cancellation of the IM3 products from the third-order term \(a_3\) by the fifth-order term \(a_5\) as seen from the following equation:

\[
\text{IM3} = \frac{3}{4}a_3V_{in}^3 + \frac{25}{8}a_5V_{in}^5 \ldots
\] (5)

While these sweet spots are good for choosing power levels with very good linearity (low IM3 power levels compared with the fundamental tones), they are also spots where a gain expansion occurs instead of gain compression. This can be understood from the fact that gain compression at high power (denoted by the \(P - 1\) dB level) is typically due to \(a_3\). When the contribution from \(a_5\) starts canceling that from \(a_3\), a gain expansion occurs instead of a gain compression. This effect is noticeable in the fundamental power at around −15 dBm in Fig. 9, where a slight dip in the fundamental power is followed immediately by a slight increase. This gain expansion could cause unexpected effects when coupled with positive feedback.

Third, the nonlinear intrinsic capacitances (base–emitter, base–collector, and substrate capacitances) in the transistors vary with varying power levels. The values of these capacitances determine the location of the poles in the NFC network impedance function. As the input power increases, the changing values of the capacitances change the impedance of the NFC. This could possibly force the poles to move from a stable region to an unstable region in the complex frequency plane, depending on the swamping impedance. Although the short circuit stability conditions were not violated at high power in this particular NFC matched antenna design, care should be taken to determine that the NFC impedance at high power satisfies stability conditions.

Further studies need to be done on high power instability to determine if it simply a manifestation of generated mixing products from extreme nonlinearity, or if the variation in device gain and parasitics cause unexpected instability issues.

VI. NFC MATCHED ANTENNA VERSUS UNMATCHED ANTENNA

To determine the true advantage of NFC matched antennas attached to a power amplifier in transmit applications, they should be compared with the unmatched antenna attached to the same amplifier. The main parameters to be compared to establish a figure of merit are the output power and the OIP3 of the two systems across the bandwidth under consideration.

The simulations were performed by attaching the non-Foster matched antenna to a measured model of an amplifier (MITEQ AM-1533) with an OIP3 of 26 dBm and a gain of 40 dB under matched conditions. The unmatched antenna was then attached to the same amplifier and two-tone simulations were performed for both (Fig. 1).

A. Gain (\(P_{\text{out}}\)) Comparison

Fig. 10 presents the simulated gain for the two systems for varying input power levels. The input power levels are very low to take into account the 40-dB gain of the amplifier.

It can be seen from Fig. 10(a) that the gain variation of the NFC matched antenna system is very similar to the gain variation shown in Fig. 5 for the NFC matched antenna by itself, indicating that the amplifier attached to the NFC matched antenna does not degrade the linearity of the system significantly. This is further reinforced in Fig. 10(b) for the gain variation of the unmatched antenna attached to the same amplifier. It can be seen that the gain does not vary for the unmatched antenna system for almost all input power levels under consideration. The average gain of the NFC matched antenna system within the designed matching bandwidth (30–135 MHz) has been computed by integrating the curves in Fig. 10(a) for different input power levels and compared with that of the unmatched antenna system for the same frequencies, as shown in Table I. A comparison of the average gain for the two systems shows that although the NFC matched antenna system has higher gain (and therefor higher \(P_{\text{out}}\)) for lower input power levels, the unmatched antenna systems delivers higher \(P_{\text{out}}\) at higher power levels. The improvement in gain with the NFC match is not significant, since the NFC design was optimized to provide the largest matching bandwidth, at the expense of tolerating some loss to ensure stability for such broad bandwidths.

<table>
<thead>
<tr>
<th>Input Power Level</th>
<th>Avg. gain for NFC matched antenna with amplifier (dB)</th>
<th>Avg. gain for unmatched antenna with amplifier (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-80 dBm</td>
<td>34.6997</td>
<td>33.7560</td>
</tr>
<tr>
<td>-70 dBm</td>
<td>34.6882</td>
<td>33.7560</td>
</tr>
<tr>
<td>-60 dBm</td>
<td>34.3335</td>
<td>33.7556</td>
</tr>
<tr>
<td>-50 dBm</td>
<td>32.0677</td>
<td>33.7489</td>
</tr>
<tr>
<td>-40 dBm</td>
<td>29.5981</td>
<td>33.6857</td>
</tr>
<tr>
<td>-30 dBm</td>
<td>27.9158</td>
<td>33.1536</td>
</tr>
</tbody>
</table>
Fig. 10. (a) Simulated gain of the NFC matched antenna system for various signal power levels. (b) Simulated gain of the unmatched antenna system for various signal power levels.

Fig. 11. (a) Simulated OIP3 of the NFC matched antenna system compared with that of the unmatched antenna system. (b) Simulated IIP3 of the NFC matched antenna system compared with that of the unmatched antenna system.

B. OIP3 and IIP3 Comparison

OIP3 and IIP3 simulations were performed for the setup shown in Fig. 1 for the bandwidth under consideration, and the results are presented in Fig. 11. In all simulations, the fundamental tones $f_1$ and $f_2$ have a 1-MHz separation. The OIP3 results shown in Fig. 11(a) indicate that the OIP3 of the unmatched antenna systems is much higher than the OIP3 of the NFC matched antenna system. The IIP3 of the unmatched antenna systems is also much higher than the IIP3 of the NFC matched antenna system across the bandwidth under consideration [Fig. 11(b)]. Therefore, the results indicate that at high power, the unmatched antenna system with the amplifier delivers higher $P_{out}$ and also has lower IM3 products in terms of better OIP3 and IIP3. However, the NFC used in all the simulations and measurements had been optimized for maximum bandwidth, and had taken advantage of low bias currents for each of the transistors ($I_c = 2.3$ mA) to ensure better stability. Since a typical brute force linearization technique is to increase the bias current in the active devices, we proceeded to examine the OIP3 and IIP3 of the NFC matched antenna at higher bias currents in the NFC.

VII. LINEARITY IMPROVEMENT TECHNIQUES FOR THE NFC MATCHED ANTENNA

On increasing the bias current $I_c$ for the two transistors in the NFC matching network by increasing the bias voltage, the OIP3 and IIP3 of the NFC matched antenna system (including the amplifier) have been found to increase almost exponentially with bias current for small initial increments in bias current, as shown in Fig. 12. The simulations have been done for a two-tone input of $f_1 = 99$ MHz and $f_2 = 100$ MHz. However, for large bias currents, the
OIP3 and IIP3 are seen to saturate. Therefore, for this particular NFC matched antenna system, it might not be possible to exceed the 20-dBm OIP3 of the unmatched antenna system for the same input frequencies shown in Fig. 11(a). This is not unexpected because the transconductance of the transistor, which determines the generated non-Foster reactance, changes drastically with bias current, and this leads to suboptimal matching and gain conditions. The midband gain of the NFC matched antenna was found to decrease as the bias current was increased above the design value of 2.3 mA. The simulations have also not taken into account the stability of the NFC at these bias conditions. At higher bias currents, achieving stability can be a challenge due to the increased gain of the transistors [11]. In [12], measured OIP3 values above 15 dBm have been reported for a non-Foster matched circuit model of an antenna, but corresponding simulations have not been shown to provide further details. Additionally, different biasing strategies (class B and class AB) should be explored in order to ensure optimum power added efficiency while ensuring a greater gain-bandwidth product and OIP3 over passive matching techniques [13], [14]. Since MOSFETs have a square-law response in their $I-V$ characteristics, there is ideally no third-order nonlinearity unlike the nonlinear response from the exponential $I-V$ characteristics of diodes in diode-based NFCs [15] and BJTs in BJT-based NFCs. Therefore, the potential advantages of a better linear performance from NFCs with the CMOS technology [16] should also be investigated.

Real-world applications require adaptive non-Foster matching circuits [17] that can match the passive antenna’s impedance under different near-field conditions. In addition, an adaptive control algorithm might also have to be developed to provide sufficient dynamic matching for different signal power levels. The design of NFCs for high-frequency applications, such as mobile phone technology, will require transistors with very low parasitics and high transition frequencies. Such applications have stringent requirements for minimizing out of band emissions, and a linearized design of the NFC should conform to those requirements.

VIII. CONCLUSION

The effects of nonlinearity in an NFC matched antenna have been identified in terms of match degradation, gain degradation, and potential instability. A performance merit has been established for an NFC matched transmit antenna by comparing it with an unmatched antenna for the same transmitting system. Simulations on overall system gain and OIP3 indicate that at low bias currents, the unmatched antenna is superior to the NFC matched antenna at high power. However, high bias currents for the NFC indicate much greater improvement in IP3. This preliminary investigation indicates that the design of NFCs for high-power applications should not only focus on the highest achievable power and efficiency, but should also analyze the generation of distortion products that are a result of the intrinsic nonlinearity and the positive feedback. The design should be a balance between power added efficiency, IP3, and gain-bandwidth product. Some studies have already been done on optimal biasing strategies to minimize dc power consumption and increase the power added efficiency of the NFC, but further studies should investigate linearization techniques for non-Foster circuits.

REFERENCES


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