ELECTRICALLY SMALL, EFFICIENT, WIDE-BAND, LOW-NOISE ANTENNA ELEMENTS

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Abstract: An investigation was performed to explore a new class of active circuit element for achieving efficient wide-band impedance matching of electrically small antennas. Conventional approaches using passive circuit elements are limited in achievable gain-bandwidth, and previous attempts to overcome this limitation with active circuits were not successful.

Transistor circuits were designed to behave as two terminal impedance elements able to violate the Foster reactance theorem and provide more versatile reactance versus frequency than passive networks. Their utility in matching small antennas was confirmed analytically, resulting, for example, in an estimated VSWR of less than 2:1 for a 100 cm dipole over the frequency range of 30 to 88 megaHertz.

Whether these circuits could actually be realized in low-loss configurations free of microwave instabilities was not known, and most of our effort was devoted to fabricating and testing a working circuit model, nominally a negative inductor, emphasizing its stability at frequencies as high as 25 gigaHertz. The circuit demonstrated non-Foster impedance characteristics from 30 to 88 megaHertz and was free of high frequency instabilities, indicating that the new class of circuits is feasible and can be evolved to enlarge the bandwidth of electrically small antennas many times.

1. Conventional wide-band matching of electrically small antennas.

All electrically small antennas, those which extend less than about 1/3-wavelength are characterized by several features:

- radiation patterns that vary slowly with frequency and exhibit a peak directivity of ~1.5 dB,
- small values of radiation resistance that increase as frequency-squared,
- large values of reactance that vary rapidly with frequency,
- limited gain-bandwidth products when matched by orthodox methods.

Small electric dipoles, small magnetic dipoles and combinations of small electric and magnetic dipoles exhibit the same fundamental properties. This discussion focuses on small electric dipoles.

Conventional wide band impedance matching incorporates matching circuits into the antenna with the purpose of obtaining maximum power transfer over a selected range of frequency. The goal is usually constant VSWR over the band. These techniques cannot improve on the antenna's circuit quality. On the other hand, they will not degrade its circuit quality if properly applied. To the extent that total power transfer is achieved over the band, an electrically small antenna can exhibit antenna gain of ~1.5 dB.

The input impedance of a thin, short electric dipole is approximated very well over a range of frequencies by an equivalent circuit consisting of the antenna's radiation resistance, its loss resistance, a large capacitive reactance and a small inductive reactance. In most instances, its loss resistance is small enough compared with the radiation resistance that it may be ignored. Figure 1 contains a Smith chart display of the impedance properties of a 100 cm dipole, showing its combination of small resistance and large capacitive reactance over the VHF-FM communications band of 30 to 88 mHz. The first step in matching such an impedance curve is to balance or resonate it by the addition of series inductance (Figure 2) with the result that (Figure 3) the midband of the frequency segment to be matched is on the resistance axis. In this example the midband frequency is 59 mHz. The next step is the addition of a shunt tuned circuit that results in an impedance characteristic (Figure 4) with a VSWR no larger than 7:1 over the range of 57½ to 60½ mHz, corresponding to a matching loss of 3.6 dB over that 3 mHz band. The parameters of the matching circuit were carefully chosen so the 'matched' 3 mHz segment of the curve is centered at Z_0, eliminating the need for the transformer section included in Figure 2. In general, a transformer will be required.

Even this modest result is obtained with great difficulty. Matching circuit elements must be high Q and their values must be obtained with reasonable accuracy. To achieve these requirements, most practitioners turn to transmission line elements which are able to provide high Q performance and accurate,

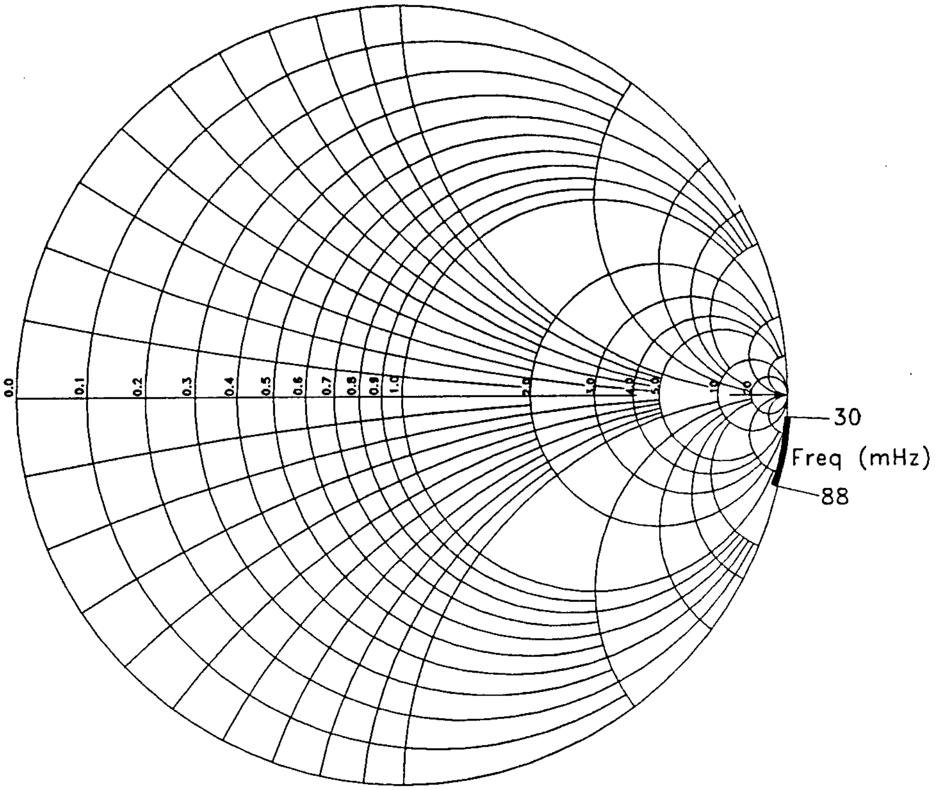


Figure 1. Impedance of
a Symmetrical Center-fed
Dipole Antenna with Total
Length of 100cm. Element
Diameters = 0.1 inch
Frequency = 30 to 88mHz
Z-zero = 50 ohms

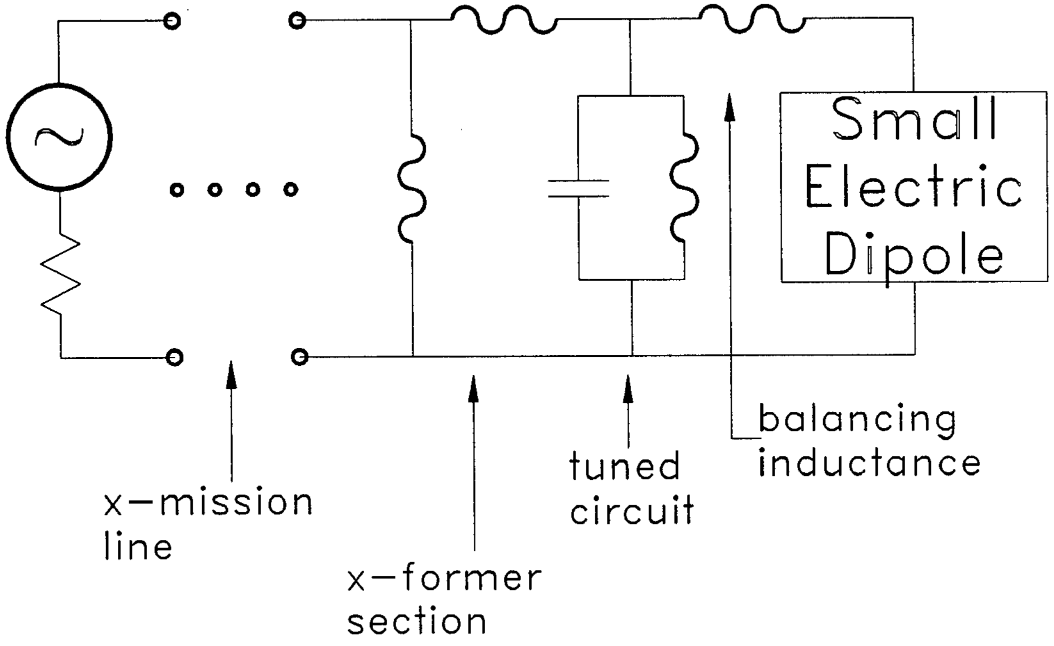


Figure 2. Conventional Matching of Electric Dipole Antenna

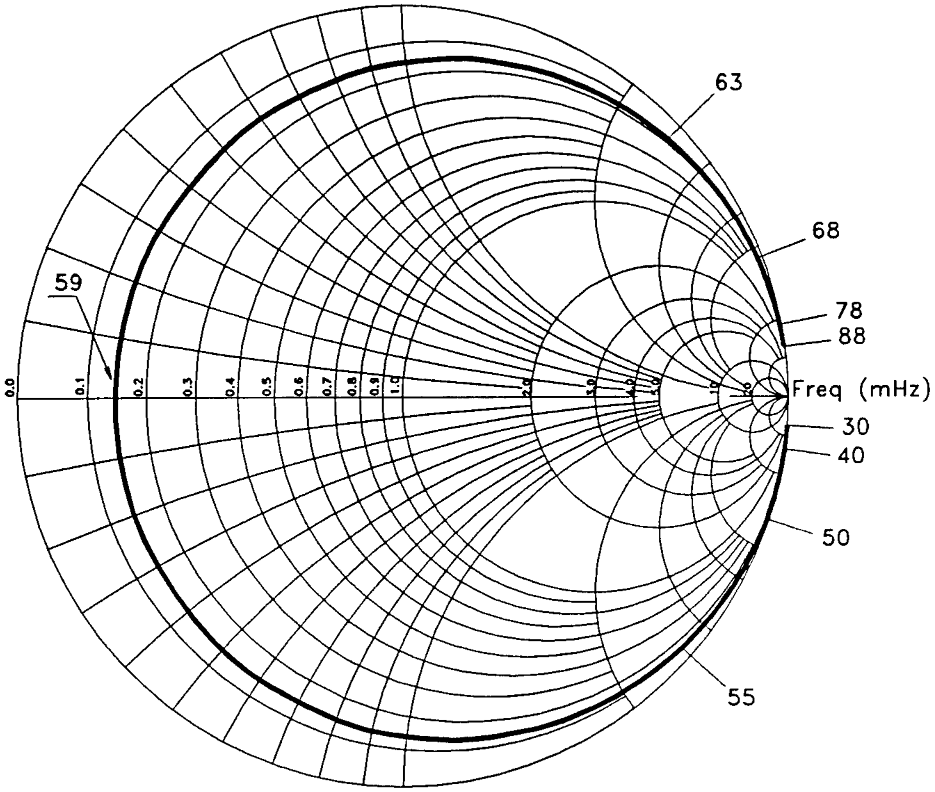
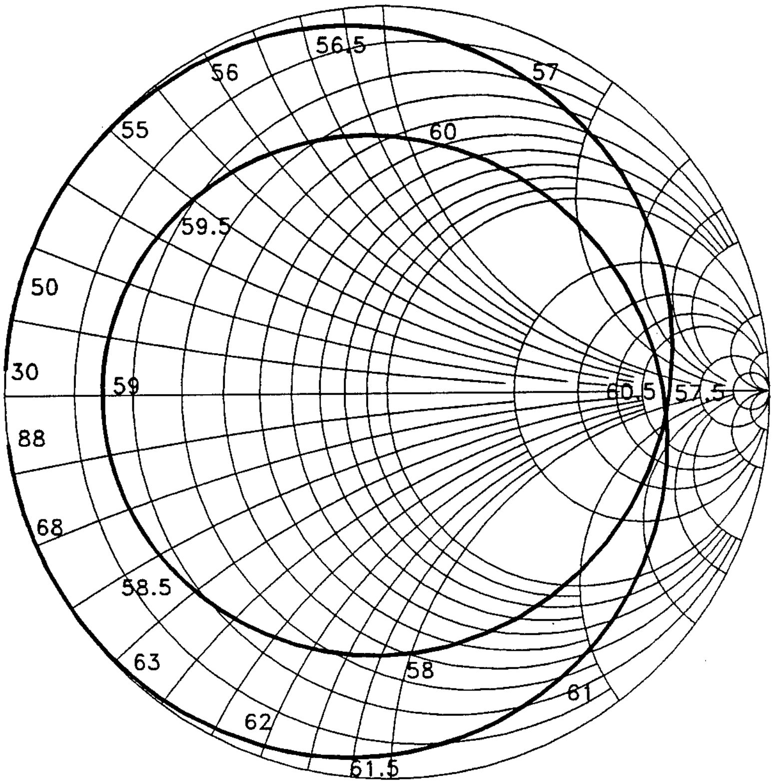


Figure 3. Impedance of a Symmetrical Center-fed Dipole Antenna with Total Length of 100cm. Balancing Series L = 2.18μHenry Element Diameters = 0.1 inch Frequency = 30 to 88mHz Z-zero = 50 ohms



Frequency (mHz)

Figure 4. Impedance of a Symmetrical Center-fed Dipole Antenna with Total Length of 100cm. Element Diameters = 0.1 inch. Matching with Series L and a Shunt Tuned Circuit Frequency = 30 to 88mHz Z-zero = 50 ohms

flexible component values, but at the expense of additional dispersions that diminish achievable VSWR. Concepts of switching among matching circuits to cover different band segments are theoretically possible, but their practicality remains an issue in most applications.

2. Non-Foster wide-band matching of electrically small antennas.

The Foster reactance theorem states that the reactance slope of passive circuits is everywhere positive. Circuit elements which could provide negative reactance slopes (non-Foster elements) would improve on the performance achievable using conventional methods many times. Elementary non-Foster components are negative inductances and negative capacitances. Our work indicates that combinations of these elementary non-Foster components can be achieved in a single active circuit, without the need to place several elementary components in tandem.

Using the same electric dipole as before, the non-Foster matching strategy is to compensate the dipole reactance with a non-Foster series circuit element and to transform the resistance level using a transformer in which one of the components is non-Foster (Figure 5). To illustrate some of the details, the antenna impedance model used is more accurate and more complex than that of a simple RLC equivalent circuit while the non-Foster reactances are modelled as purely negative L or negative C. In the first step, a circuit consisting of negative L and negative C is connected in series with the antenna, and the values are chosen so that the end points of the resulting characteristic lie on the resistive axis (Figure 6). Had the antenna impedance been faithfully represented as a simple RLC series circuit, the resulting characteristic would have stayed on the resistive axis across the entire band, reflecting the frequency-squared variation of radiation resistance.

In the second step, an impedance transformer consisting of a series negative inductance and a shunt positive inductance of equal magnitude is employed as indicated in Figure 5 with the resulting impedance characteristic illustrated in Figure 7. This type of transformer has the property of converting a frequency squared resistance to a fixed value, a most fortuitous circumstance for antenna designers. Once again, had the antenna impedance been faithfully represented by a simple RLC circuit, with resistance increasing as frequency squared, the final result would have been a point in the center of the chart. Interchanging the inductors in the transformer leads to a similar result (Figure 8).

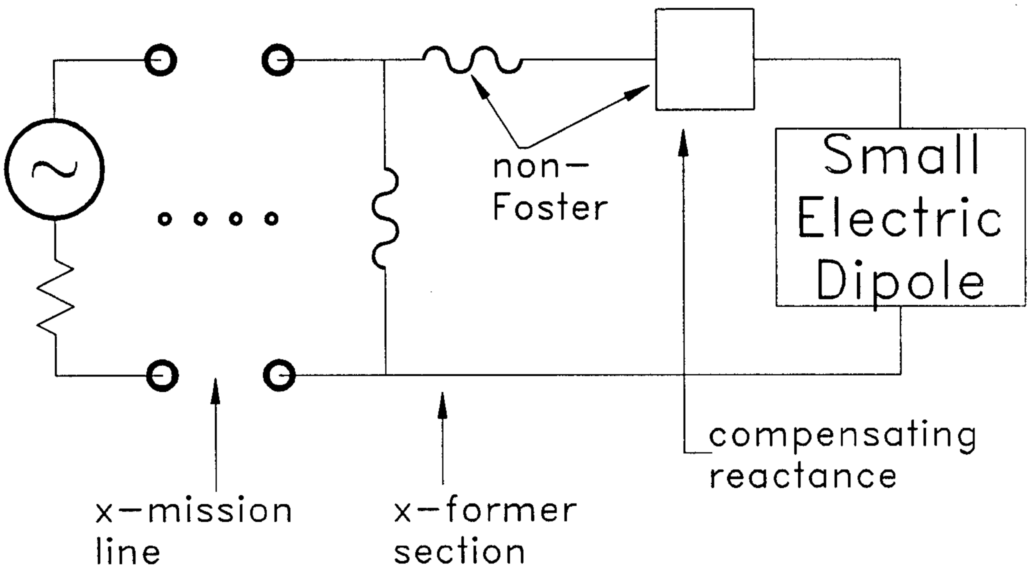


Figure 5. Matching of Electric Dipole with non–Foster Reactances

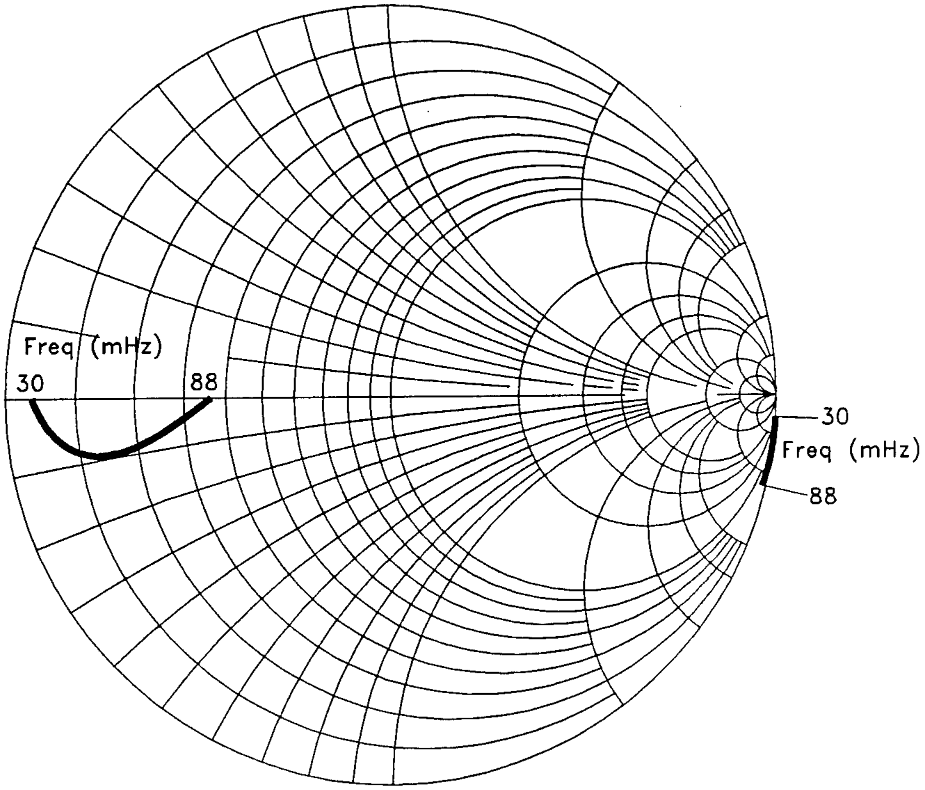


Figure 6. Impedance of a Symmetrical Center-fed Dipole Antenna with Total Length of 100cm. Element Diameters = 0.1 inch
Series L = −0.370 μHenry
Series C = −2.861 pFarad
Frequency = 30 to 88mHz
Z-zero = 50 ohms

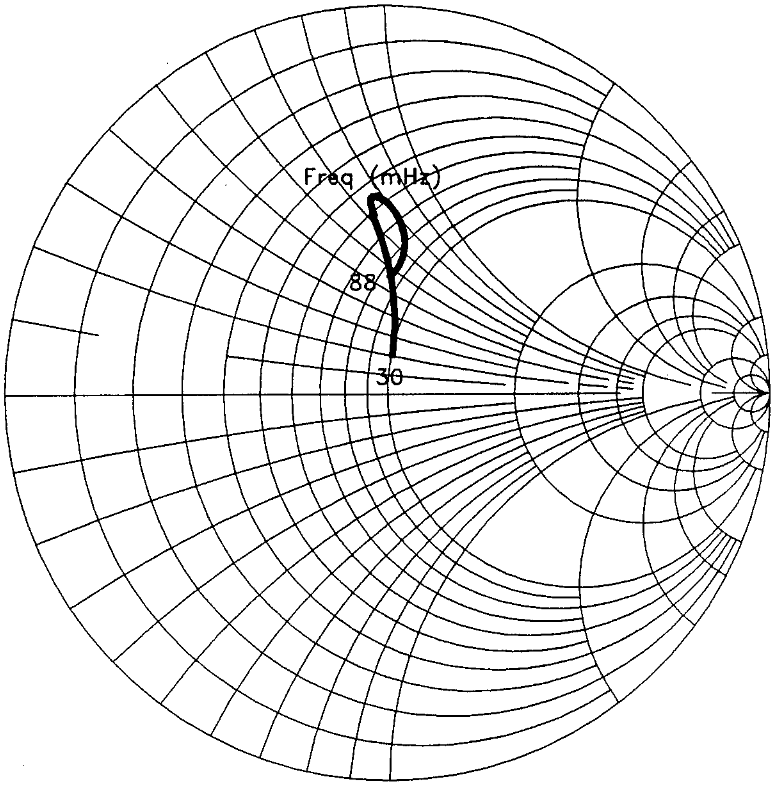


Figure 7. Impedance of the Center-fed Dipole with Series L = −0.370 μHenry Series C = −2.861 pFarad and a transformer with Series L = −50 μHenry and Shunt L = +50 μHenry Frequency = 30 to 88mHz Z-zero = 50 ohms

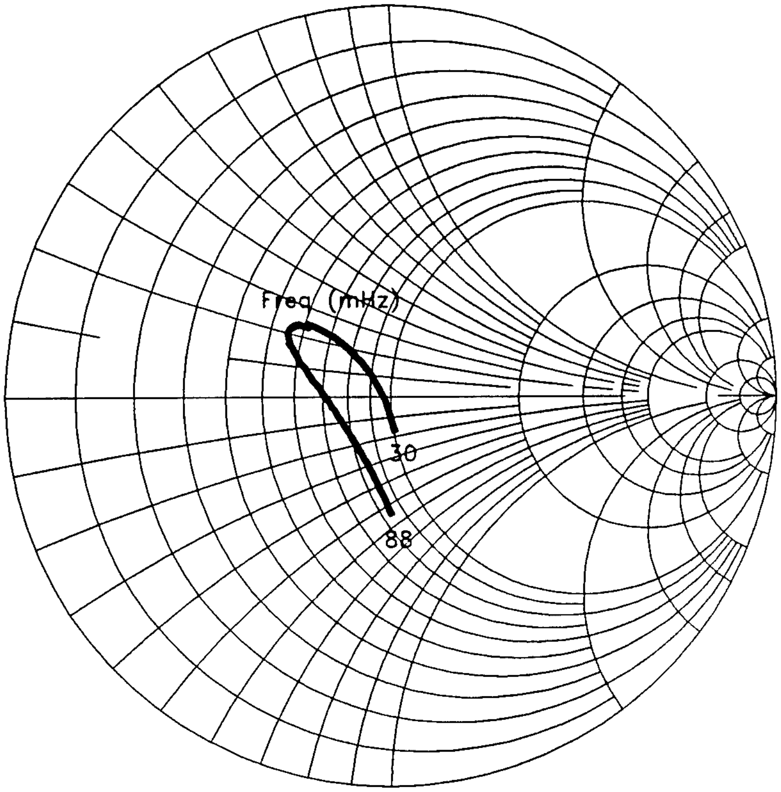


Figure 8. Impedance of the Center-fed Dipole with Series L = −0.370 μHenry Series C = −2.861 pFarad and a transformer with Series L = +50 μHenry and Shunt L = −50 μHenry Frequency = 30 to 88mHz Z-zero = 50 ohms

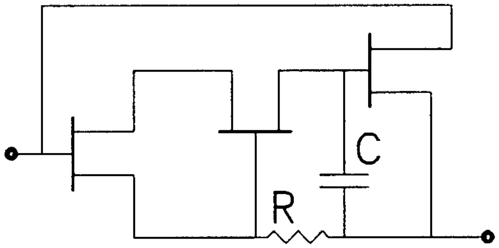
3. Non-Foster Reactance Circuits.

What was not clear at the beginning of our effort was whether, or how well, circuit components able to improve the performance of electrically small antennas could actually be realized. A survey of work in progress turned up a large body of theoretical activity directed at promising configurations of FET amplifiers. All investigators identified wide-band stability as the issue of major concern, and some suggested that monolithic fabrication would be needed to ensure it. Stability problems were clearly the reason for the absence of reports on circuit implementations. We found no evidence of even one working model, excepting for an operational-amplifier based circuit whose designers strongly recommend FET techniques over op-amp approaches.

Our own analyses confirmed that wide band stability was the major issue; circuits designed to provide low-loss reactances at frequencies near 100 mHz required the use of FET devices with positive gain at 25 gHz, and low loss reactive circuit designs were highly susceptible to high frequency oscillation. Substantive progress demanded more information than we could uncover, so we devoted most of our contract effort to achieving a stable non-Foster circuit.

The circuit for this demonstration was selected from a family of circuits proposed by Khoury [1], in which 'current conveyors' are connected to achieve desired terminal properties. The circuit selected for implementation (Figure 9) used three MESFETs. In active network synthesis, three terminal networks called current conveyors have proven to be very useful in synthesizing various functions. The admittance matrix of a current conveyor has the form illustrated in Figure 10. Depending on the connection, it can represent a number of two port devices, including the voltage controlled current source, the voltage controlled voltage source, and the current controlled current source.

Microwave hybrid chip and wire construction was used because it permits tight control of the circuit parasitics able to induce oscillation. The circuit was built on 0.010 inch thick alumina substrate with via holes placed through the substrate to achieve low inductance grounds as needed. A photograph of the circuit is included (Figure 10). Spectrum analyzer measurements from dc to 22 gHz assessed the circuits stability, and vector network analyzer measurements in the 0.5 to 100 mHz range determined its impedance properties. The measurements showed the circuit to be entirely free of microwave oscillations. After a series of adjustments to reduce the level of low frequency oscillations with spectral content up to 21 mHz, it was possible to characterize the circuit's



$$Z_{in} = -sC\,\frac{1/r_{ds} + g_{m2}}{g_{m1}\,g_{m2}\,g_{m3}}$$

Figure 9. Non-Foster Circuit Based on Current Conveyor

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}$$

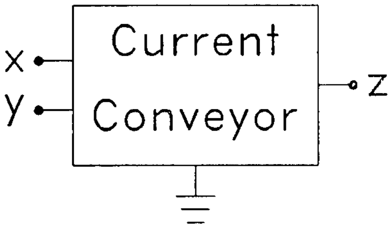


Figure 10. Admittance Matrix of Current Conveyor

important performance parameters. Two important results were obtained:

- The sought after, non-Foster, impedance behavior was observed. The measured impedance characteristic (Figure 11) rotated counterclockwise with frequency.
- No microwave instabilities were observed. Microwave oscillations have been the major impediment to realizing circuits of this kind, and demonstration of a working circuit free of microwave instabilities is a very big step in establishing their credibility.

4. Antenna Applications.

Non-Foster techniques can be usefully applied to reduce an antenna's extent whenever the troublesome size is the result of a gain-bandwidth requirement as opposed to a directivity requirement. They can be useful for transmitting sites for all services from ELF to VHF for ground installations, probably through L-band for vehicular installations, particularly on helicopters and stealthy aircraft. For receiving applications they can be applied usefully to expand bandwidth and/or reduce size whenever receiver noise is an important limitation, certainly including frequencies at and above HF.

A few areas where these methods appear to be particularly appropriate include:

- Aircraft and other vehicular installations where the resulting reductions in size of external or subsurface antennas can be very useful. Applications include communications, navigation, signal intercept and countermeasures at HF, VHF, and UHF.
- Global communications and/or navigation system transmissions at and below HF, including AM broadcasting.
- Man portable applications include relatively low frequency field radio service as well as local area telephony, data and entertainment distribution systems. Note that in any free space communications system, if we can elevate the gains of both transmit and receive antennas to near unity, power transfer becomes proportional to frequency-squared. In the example of 900 mHz versus 48 mHz local area data distribution, the lower frequency system enjoys a 13 dB advantage.

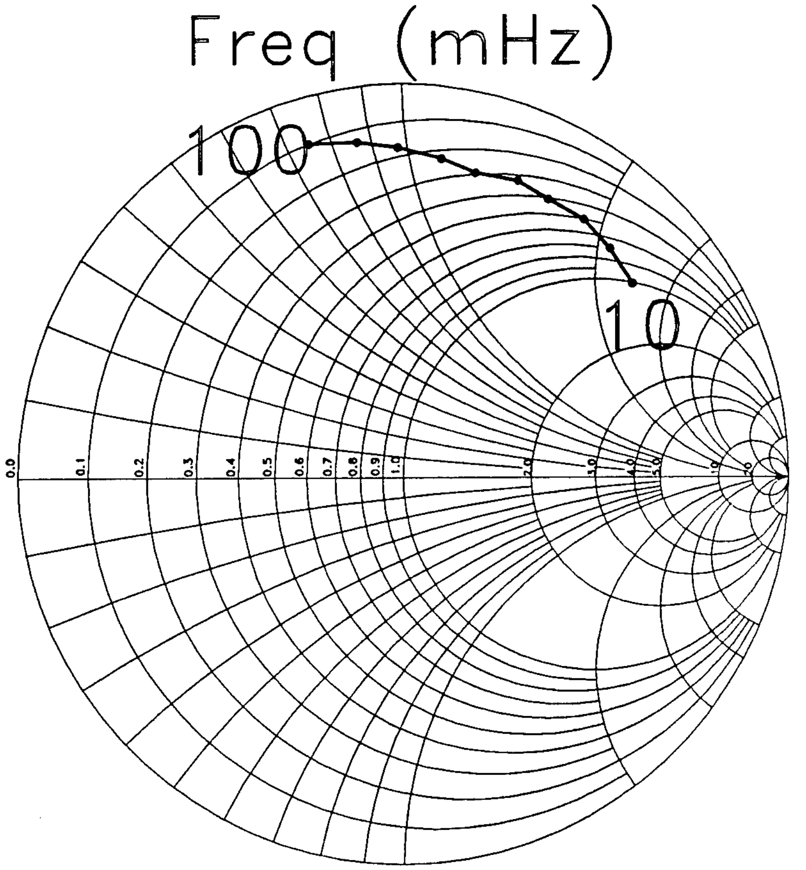


Figure 11. Measured Impedance of Proof of Concept non-Foster Reactance Circuit Frequency = 10 to 100mHz Z-zero = 50 ohms

5. Recommended Future Tasks

At the onset of this effort, we uncovered large amounts of literature describing the performances and attributes of current conveyor circuits, and we anticipated rapid progress toward their application to wide-band matching of electrically small antennas. Instead, we found no evidence of demonstrated performance at radio frequencies, and that these circuits had become a focus for purely theoretical study. We successfully performed a proof of concept experiment and resolved the question of credibility: they do perform in accordance with prediction models, and they can be implemented as radio frequency, low-loss, non-Foster reactances despite their recognized potential for high frequency, parasitic driven, instability. Although an enormously successful proof of concept, it stopped well short of creating enough insight and understanding to support confident design work. That confidence can be built only through additional development tasks.

Some of the parameters that need to be resolved experimentally in evaluating the utility of these circuits, after the big two of STABILITY and LOSS is their noise power generation, their linearity, issues that determine their frequency limits and achievable bandwidth, and power handling.

Rapid growth in understanding the behavior of these circuits can be achieved by designing, fabricating and testing additional circuits based on the thin film, microwave hybrid chip and wire construction method reported here, ensuring control of the parasitics that can cause unforeseen oscillations. The first circuits would be variations of the proof of concept unit, incorporating adjustments: to eliminate entirely its low frequency oscillation; to adjust various bias levels and resistance values to ensure the continued absence of microwave oscillations and to move the impedance trajectory closer to the edge of the Smith chart. Alternative topologies should be designed to demonstrate various combinations of desirable circuit behavior such as, for example, series and shunt negative inductors, negative capacitors, negative L - negative C tuned circuits, and other more general non-Foster reactances.

These hardware developments ought to integrate development and validation of analysis models for characterizing all important performance parameters, including linearity, noise generation and frequency limitations.

While the chip and wire construction method is useful for preliminary circuit evaluation, it is important to generate and evaluate non-Foster circuit elements using fabrication methods more suited to low-cost, high volume production.

An extremely useful task would be to fabricate several fully integrated printed circuits containing the transistor circuit elements, providing for external attachment of sizeable components or other components for which value adjustments via replacement can be useful. This unit would provide for external application of bias voltages and include internal test points.

These steps should be paralleled by evolution, fabrication and testing of surface-mount circuits. With this approach, because the circuits must be more sizeable and they provide for less control of the stray capacitances, the stability issue may be far more difficult to resolve. On the other hand, they are cheaper, more quickly obtained, and more easily modified over and over again, permitting an iterative, more experimental approach to achieving stable, low loss circuits.

Given the availability of the requisite non-Foster component(s) available from earlier tasks, the next task would be to design, fabricate and measure the impedance/efficiency properties of several antennas that have been matched with the aid of non-Foster circuit elements over substantial frequency extents, e.g., 30 to 88 mHz, 2 to 30 mHz, 2 to 88 mHz, etc.

A longer range task is evolution of non-Foster components capable of supporting transmitter power levels. This task may stimulate the evolution of specially tailored high frequency, high power transistors.

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7.0 References.

[1] S. El Khoury, "The Design of Active Floating Positive and Negative Inductors in MMIC Technology," *IEEE Microwave Guided Wave Letters,* vol. 5, no. 10, October, 1995

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