Compact Mixer-Based 1–12 GHz Reflectometer

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***Abstract*—Compact, broadband, and low-cost reflectometry is important for array-based microwave imaging and sensing applications in biology and medicine. To achieve broadband performance, we use cascaded bridged-T attenuators incorporating mixers to replace directional couplers in a new reflectometer design. In this letter, we present the design of the reflectometer and the associated calibration technique. We evaluate the performance of the reflectometer in characterizing two different load impedances and compare results favorably with those of a commercial vector network analyzer.**

***Index Terms*—Attenuators, mixers, reflectometer, ultrawideband (UWB) microwave imaging.**

I. Introduction

ULTRAWIDEBAND (UWB) microwave radar imaging and sensing techniques are being developed for a variety of medical and biological applications, such as early-stage breast cancer detection [1]–[5] . These techniques involve the use of antenna arrays for the transmission of probing signals and the reception of scattered signals. Such detection techniques require reflectometer circuits that measure the ratio of the reflected wave to the incident wave. We have recently demonstrated that a monostatic UWB microwave system comprised of a mechanically scanned UWB antenna and a commercial vector network analyzer (VNA) serving as the reflectometer can be used with space-time microwave imaging algorithms to detect synthetic tumor masses with diameters of less than 5 mm in simple multilayer breast phantoms [3]. For clinical applications of UWB microwave imaging, electronically scanned arrays of antennas would be required, with each antenna possibly connected to its own reflectometer.

In this letter, we explore the feasibility of developing inexpensive and compact microwave reflectometers—functional subsets of expensive VNAs—capable of array deployment for low-cost UWB microwave imaging and sensing applications. The directional couplers used in commercial VNAs are three-dimensional (3-D), precision-machined components which cost several thousand dollars each. Planar directional couplers [6] for use in low-cost VNAs lack the broadband capability needed, and they can become physically large (i.e., over 5-cm long at frequencies around 1 GHz). In our approach, we use bridged-T attenuators incorporating mixers, which maintain the characteristic impedance of the system, as alternatives to expensive 3-D directional couplers or low-performance planar directional couplers. Our approach allows for a significant size reduction in the reflectometer, enabling compact arrays.

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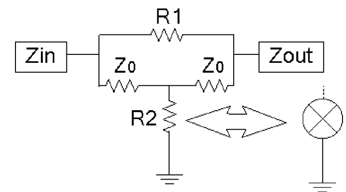


Fig. 1. Diagram showing how a mixer is incorporated into the 6-dB bridged-T attenuator circuit. R1 and R2 are defined as Z_0.

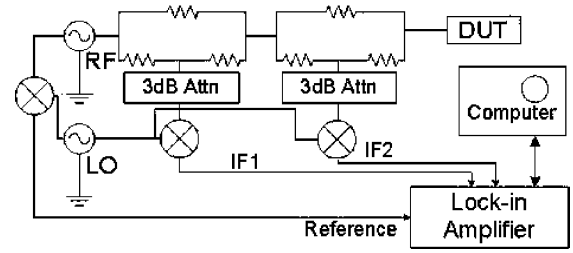


Fig. 2. Circuit diagram for cascaded bridged-T attenuators used in a one-port reflectometer. 3-dB attenuators were inserted for forged mixer matching.

Many approaches to accurate microwave reflectometry have been reported, and developed for decades [7]–[14]. In most modern VNA measurement schemes, however, directional couplers separate the incident wave a from the reflected wave b to calculate the complex reflection coefficient, $\Gamma = b/a$.

II. Theory and Design

As shown in Fig. 1, we employ 6-dB bridged-T attenuators. The 50-Ω resistors to ground (R2 in Fig. 1) are replaced by frequency mixers with similar input impedances. These modified bridged-T attenuators are inserted in the place of the directional couplers of commercial VNAs, as shown in Fig. 2. The mixer input impedance was assumed to be equal to Z_{o} (50 Ω) over all frequencies. Any mismatch would generate standing waves inside the bridged-T attenuator circuit, which would subsequently limit the accuracy of the reflectometer. To overcome this problem, 3-dB attenuators were inserted (Fig. 2) at the mixer inputs. The 3-dB attenuators provide a much better match with the bridged-T attenuators, and thus reduce the effect of standing waves by attenuating the reflected wave from the improperly matched mixers.

In the same manner that a distributed amplifier achieves broadband gain by absorbing the parasitics of the gain elements into a synthetic transmission line, this new reflectometer configuration enables a broadband direct measurement of the complex reflection coefficient by absorbing the parasitics of the

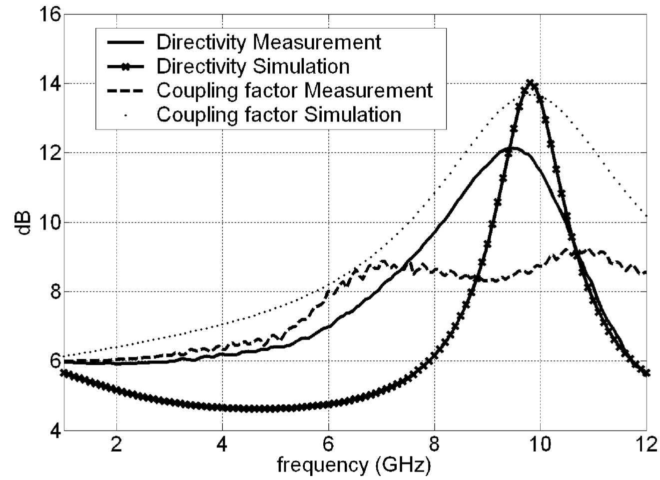


Fig. 3. Measurement and simulation of directivity and coupling factor of cascaded bridged-T attenuators.

mixer. It incorporates mixers as sensitive detection elements, while dramatically reducing the effects of parasitic resistance, since the 50-Ω impedances of the mixers become part of the attenuators.

With the assumption of perfect source matching, there exist one forward signal from the radio frequency (RF) and one reverse signal reflected from the device under test (DUT). These two signals are combined and resulting intermediate frequency 1 ($IF1$) and $IF2$ in Fig. 2 with the following:

$$IF1 = \left(\frac{1}{2}\cdot V + \frac{1}{8}\cdot V \cdot \Gamma e^{j2\theta}\right)\cdot Ae^{j2\theta'} \quad (1)$$

$$IF2 = \left(\frac{1}{4}\cdot \mathrm{V}e^{j\theta} + \frac{1}{4}\cdot V \cdot \Gamma e^{j2\theta}\right)\cdot Be^{j2\theta''} \quad (2)$$

where V is the RF source voltage and θ is the line delay between the DUT and the end of the system. $IF1$ and $IF2$ both have the same intermediate frequency in kilohertz or megahertz range. The terms $Ae^{j2\theta'}$ and $Be^{j2\theta''}$ are introduced into $IF1$ and $IF2$ in order to account for the differences between the two mixers and the electrical length differences for the cables connecting the mixers and the lock-in amplifier. In comparing with a commercial VNA measurement scheme, we note that $IF1$ corresponds most closely to incident wave, a, and $IF2$ to reflected wave, b. However, both $IF1$ and $IF2$ depend on V and Γ at the same time.

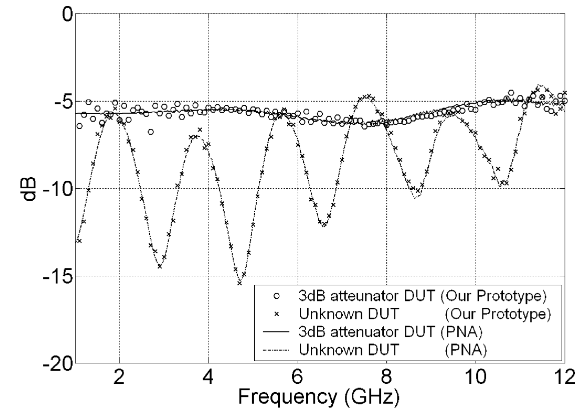
We extract an uncalibrated Γ_{raw} by manipulating $IF1$ and $IF2$ as follows:

$$X\cdot(IF1)-(IF2)=\Gamma_{\mathrm{raw}}. \quad (3)$$

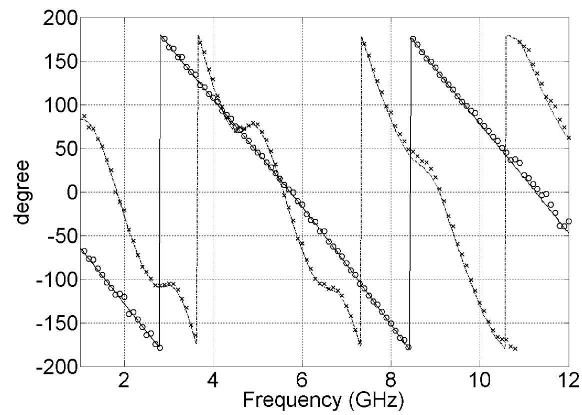
If the DUT is 50 Ω (matched to the Z_0), X can be found at each frequency of interest by setting $\Gamma_{\mathrm{raw}}=0$ in (3). We then apply the one-port calibration equations [15] to convert Γ_{raw} to S_{11}.

III. Fabrication and Measurement

We fabricated bridged-T attenuators on Rogers RO3010. The size of the circuit board is relatively large (2 cm $\times$ 2 cm) in order to accommodate the connectors. Since this was in place of directional couplers, coupling factor and directivity were of interest. As seen in Fig. 3, the coupling factor was 7 dB $\pm$ 1.5 dB, and the minimum directivity was 6 dB. In the simulation, any cross-coupling between devices is ignored, and this could generate discrepancies between simulation and measurement results. However, the measured values show a flatter coupling factor and larger directivity than the simulation.



(a)



(b)

Fig. 4. (a) Magnitude and (b) phase plot of the reflection coefficients obtained with our reflectometer prototype (shown by the discrete data markers) and an Agilent E8364A PNA (solid lines). The impedances of the DUTs chosen for this performance evaluation were "3-dB attenuator with open termination" and "unknown."

We used Marki M1–0212 mixers that cover 2 to 12 GHz and a SRS 844 RF lock-in amplifier to collect $IF1$ and $IF2$. Since the lock-in amplifier had only one input port, and a reference port, we measured $IF1$ while $IF2$ was terminated with a matched (50 Ω) load, and vice versa. The RF and longitudinal oscillation (LO) were swept from 1 to 12 GHz with a step size of 100 MHz. The RF input power was +9 dBm and the LO power was +16 dBm with a 10-MHz IF. We note that wider frequency ranges would be possible with wider-band mixers.

Mechanical open, short, and load standards were used from an Agilent 85 033D calibration kit. The calibration procedure explained in Section II was applied to obtain S_{11}. An Agilent E8364A Performance Network Analyzer (PNA) was also calibrated using the same calibration kit for the purpose of making a comparison.

Two different DUTs were measured. One had an open-ended 3-dB attenuator, and the other was an "unknown"—a 25-Ω standard and a 50-Ω standard in parallel with additional connectors. We observed reasonably good agreement ($< \pm 0.5$ dB difference) between the performance of the PNA and our prototype reflectometer (Fig. 4). However, at some frequencies, the variation in magnitude of the reflection coefficient was larger than 0.5 dB.

IV. Conclusion

We have demonstrated a new approach to a compact and inexpensive reflectometer. We used bridged-T attenuators in place of 3-D directional couplers or planar directional couplers. Measurements comparing our reflectometer with the Agilent E8364A show less than 0.5 dB of difference in reflection measurements. With additional improvements in the matching circuits and greater integration, we will be able to further reduce the cost and size of the reflectometer. This design may serve as a practical alternative to commercial VNAs for a variety of array-based sensing applications that require portable, low-cost reflectometers. Furthermore, this approach can be extended to multiport network analyzers.

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