Two New Six-Port Reflectometers Covering Very Large Bandwidths

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***Abstract*—This paper presents two new structures for six-port reflectometers with very large operating bandwidths of more than three decades, using a combination of lumped reflectors and transmission lines. Circuits working over a range of 2 MHz to 1300 MHz and 2 MHz to 2200 MHz have been built using inexpensive passive surface mount elements and Schottky detector diodes. Comparing results obtained from the new proposed structures with those obtained from a commercial network analyzer showed a worst case absolute value of 0.020 for the complex difference between the measured reflection coefficients. A convenient calibration procedure, for the entire band, is proposed using three standards and four approximately known loads.**

***Index Terms*—Calibration procedure, diode detector linearization, large bandwidth, network analysis, reflection coefficient measurement, six-port reflectometer, temperature correction.**

I. Introduction

The six-port reflectometer (SPR) [1], [2] is a passive linear device that measures the complex reflection coefficient Γ of a device under test (DUT) using four power readings, followed by a mathematical treatment of the data. Customarily, one detector (by means of a directional coupler) samples the power level of a source generator connected to one of the ports, and three detectors sample superpositions of the incident and reflected signals of the DUT, where each combination must be different from the others. The SPR circuit can be characterized by 11 real parameters which are determined prior to the measurement of the DUT by a calibration procedure. A minimum number of standards and other loads for this calibration is desirable. A rough estimate of the performance of the SPR can be made with the concept of the so-called q-points. Using four power readings, and therefore three power ratios, the value of Γ is determined as the intersection of three circles. The centers of these circles are the q-points which depend on the 11 SPR parameters (i.e., the structure of the SPR) and must be well-positioned (the optimum is $|q_i| \approx 1.5$ and $\arg(q_i) - \arg(q_j) \approx 120°$) for accurate measurements. This is difficult to realize over a large bandwidth; the SPR's known to us so far reach a maximum of about two decades by using either lumped reflectors [3] (80 to 7000 MHz) or sophisticated 3 dB quadrature couplers [4] (250 to 26 500 MHz).

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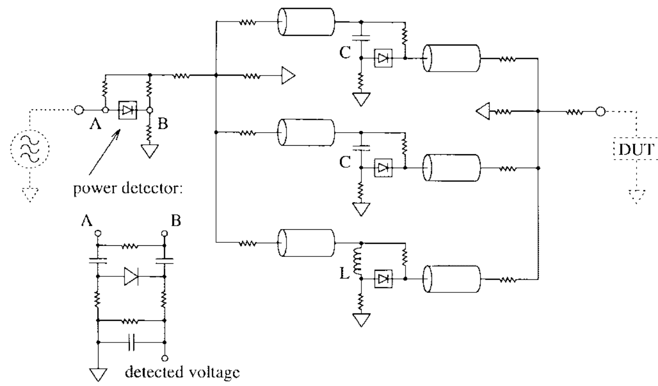

Fig. 1. Schematic of the first new six-port structure (with detailed view of a power detector).

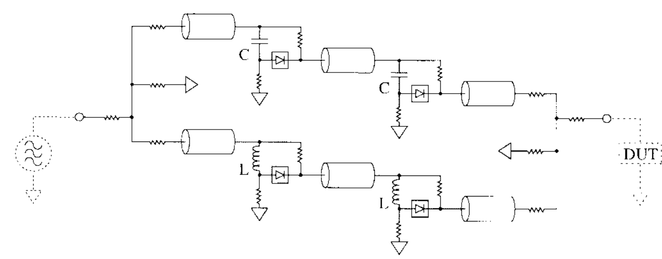

Fig. 2. Schematic of the second new six-port structure (without explicit reference detector).

In this paper, the concept of lumped reflectors is extended to cover larger bandwidths. The lumped element reflector bridges for every detector [5] are separated by transmission lines giving an additional phase shift and resulting in a bandwidth enlarged by about a decade. Furthermore, one of the new SPR's contains no explicit reference detector, this is taken into account by a special mathematical algorithm. As the commonly used calibration procedures are generally not well suited for lower frequencies nor for covering multidecade bandwidths, we will present a robust calibration algorithm which needs only seven loads to cover the entire band.

II. The Reflectometer Structures

Figs. 1 and 2 show the two newly developed SPR structures. The behavior of a six-port reflectometer can be described by the q-points as [1]

$$P_i = \alpha K_i |\Gamma - q_i|^2; \quad i = 3, 4, 5, 6 \tag{1}$$

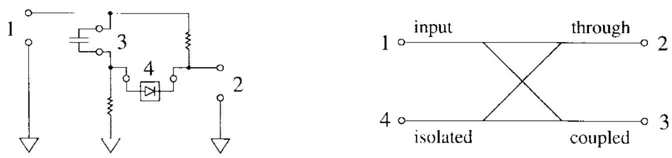

Fig. 3. Schematic of the reflector bridge (left) and the equivalent directional coupler (right).

where P_i is the detector power reading, Γ is the reflection coefficient of the DUT, α represents the source power level and the K_i and q_i are three real and four complex calibration constants (one K_i may be chosen equal to one). Once the calibration constants are known, (1) is solved for the unknowns α, $\mathrm{Re}\,\Gamma$, $\mathrm{Im}\,\Gamma$. For a network where all ports are matched, the q-points can be represented by means of the scattering parameters S_{ij} as $q_i = -S_{i1}/(S_{i2}S_{21})$, where the source and the DUT ports are indicated by 1 and 2, respectively. Therefore, the q_i can be well-spaced by properly adjusting the ratio S_{i1}/S_{i2}. In the second SPR structure (Fig. 2) there is no reference detector, and the task of determining the source power level is accomplished by the series arrangement of two detectors.

The reflector bridge (Fig. 3) [5] acts like a directional coupler: if the source, the DUT, a reactance (C or L), and the power detector are connected to four ports designated by 1 to 4, respectively, then ports 1 and 4 are isolated from each other, as well as ports 2 and 3. However, a signal coming from the DUT reaches the detector (port 2 to 4) and a signal from the source is reflected by the reactance (port 1 to 3) with a specific phase shift and, thereafter, reaches the detector (port 3 to 4), too. That is, the reactance adds a phase shift to the signal coming from the source before it is superimposed at the detector with the signal from the DUT. Using different reactances for different reflector bridges results in different phases of the corresponding q-points.

At low frequencies, where effects due to transmission lines can be neglected, a reflector bridge containing a capacitor C results in a q-point phase of $2\cot^{-1}(\omega C Z_0)$, while an inductor L results in $-2\tan^{-1}(\omega L/Z_0)$, where ω is the angular frequency and Z_0 is the characteristic impedance of the reflector bridge. At least three reflector bridges have to have different phase states. Therefore, the SPR starts to work at low frequencies when the phase difference between the reflector bridges corresponding to q_3 and q_4 is at least 30° (Fig. 5). Without the effect of transmission lines, the upper band edge is reached when all capacitors are almost short-circuited and the inductors act as open circuits. But in the proposed SPR structures, each detector has an additional and specific phase shift at higher frequencies due to carefully adjusted transmission lines (Figs. 1 and 2) the lengths of which were optimized by simulation. This expands the operational bandwidth by about a decade.

The SPR's were built using surface mount elements and zero-bias Schottky diodes on a 62.5 mil substrate with permittivity 2.5 and dimensions 42 × 42 mm^2. In order to obtain a 50 Ω match, the three reflector bridges of the SPR shown in Fig. 1 are working on a characteristic impedance of 150 Ω,

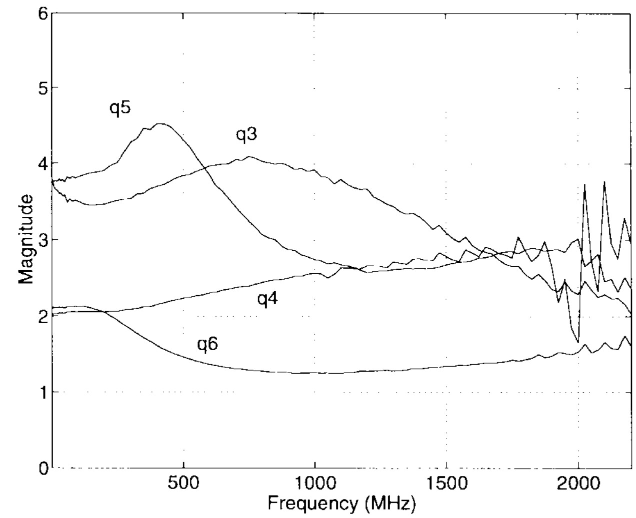

Fig. 4. Magnitudes of the measured q-points of the six-port reflectometer shown in Fig. 2.

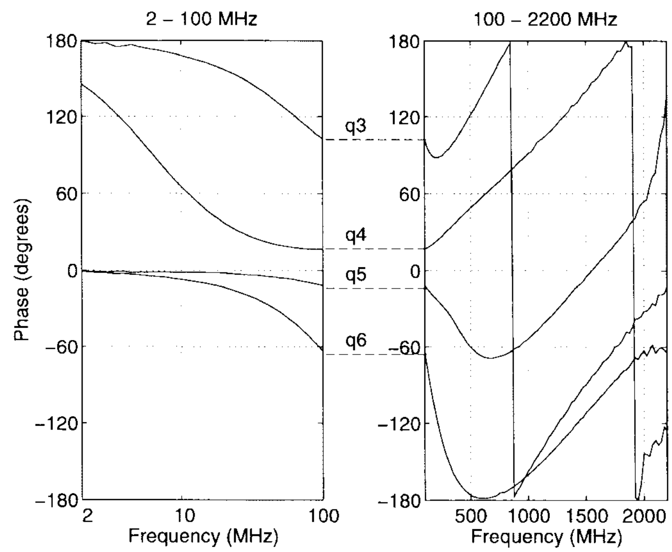

Fig. 5. Phases of the measured q-points of the six-port reflectometer shown in Fig. 2.

which results in very narrow transmission lines. The SPR in Fig. 2 has two branches in parallel with two reflector bridges each. Matching to 50 Ω is achieved with a more convenient characteristic impedance of the branches of 100 Ω. Both circuits employ T-type attenuators to prevent resonances between branches. As a result, the overall attenuation $-20\log S_{21}$ of the SPR in Figs. 1 and 2 is about 20 dB and 15 dB, respectively.

Figs. 4 and 5 show the measured q-points of the second SPR structure (Fig. 2), they are always well separated in phase and/or magnitude. In particular, where $\arg(q_i) \approx \arg(q_j)$, which occurs at the lower band edge and close to 1000 MHz, the concerned q-points show well distinguished magnitudes and therefore the function of the SPR is not affected. Below 2 MHz, calibration and measurements fail since all q-points are almost collinear. The SPR structure of Fig. 1 shows a comparable behavior to that of Fig. 2 inside its operation bandwidth, i.e., 2 MHz to 1300 MHz.

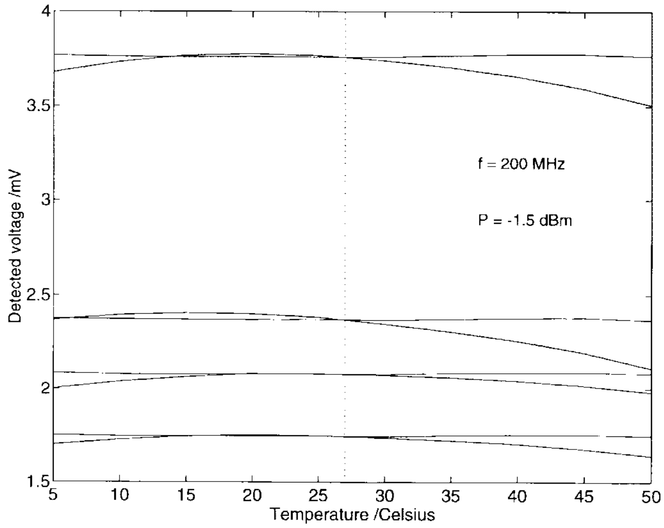

Fig. 6. Detected voltages at the four power detectors as a function of temperature. The almost straight lines represent the corrected values interpolated from the lookup-tables.

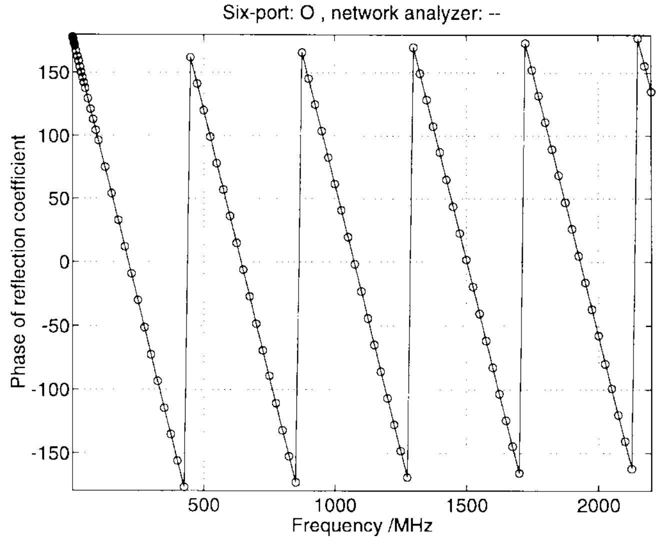

Fig. 7. Phase of the reflection coefficient of a test load, measured with the six-port reflectometer shown in Fig. 2 (circles) and a commercial network analyzer (solid line).

III. Linearization and Calibration

Linearization of the diode detectors is essential, because a diode shows a linear relationship between the applied power and the output voltage only at very low input signal levels. We linearize each detector's response at one frequency (200 MHz) using the method described in [6]. In addition, the transfer function of a diode detector depends strongly on temperature [7]. A correction factor taking into account the deviation due to the temperature is interpolated from lookup-tables. Each diode's temperature characteristic has to be tabulated separately. Fig. 6 shows that this procedure successfully corrects the detected voltages at the different temperatures to the values that would have been measured at 27 °C.

Thereafter, the 11 calibration constants are calculated in two steps. Seven loads are used for this: three standard loads ("open," "short," and "match") and four additional loads which are approximately known, i.e., they are measured at some frequency points with a network analyzer. These four loads consist of short microstrip lines terminated in lumped coils or capacitors. Their reflection coefficients have a magnitude of almost one, while the phases of at least two additional loads are well different from 0° and 180°, i.e., different from "open" and "short," at all frequencies.

In the first step of the calibration procedure, each detector is calibrated separately. Assuming a constant source power level during the calibration (small deviations will be taken into account later when only ratios are used), we can set $\alpha = 1$ in (1). Then we have, for each detector, at least four independent equations derived from (1)

$$\frac{1}{2}\left[|\Gamma|^2 + |q_i|^2\left(1 - \frac{P_i}{P_i^{\mathrm{match}}}\right)\right] = \mathrm{Re}\,\Gamma\,\mathrm{Re}\,q_i + \mathrm{Im}\,\Gamma\,\mathrm{Im}\,q_i. \tag{2}$$

Observing the constraint $|q_i|^2 - (\mathrm{Re}\,q_i)^2 - (\mathrm{Im}\,q_i)^2 = 0$, (2) is solved for q_i in a least square sense. Then, the K_i are found from (1).

In a second step, the detectors are calibrated against each other. The 11 calibration constants are divided in two groups [2]. Five real constants describe a constraint equation which contains only power ratios. As this equation is cubic in the five unknowns, a good starting point is required for an iterative solving-algorithm. The K_i and q_i obtained in the first step of the calibration process are easily transformed to the unknowns of this cubic equation and serve as starting point for solving the latter with the nonlinear Newton's method. Once these five calibration constants are known, the remaining six constants describing a bilinear transformation [2] are readily determined using the "open," "short," and "match" standards.

IV. Results

Measurements were performed on transmission lines of different lengths, combined with attenuators and "open" and "short" standards. The results were compared with measurements made with commercial network analyzers.

Both six-port structures have comparable performances. As an example, Figs. 7 and 8 show the reflection coefficient of a short-circuited transmission line, measured with the second SPR (Fig. 2) and a commercial network analyzer. Good agreement of the results is shown. For a multitude of test loads, largest values of the differences between these measurements (magnitude of the complex difference) are smaller than 0.015 at frequencies below 1000 MHz, and around 0.020 at higher frequencies. Due to the temperature correction applied, the performance does not degrade with changing temperatures, the SPR functions equally well over the whole range from 5 °C to 50 °C.

For small reflection coefficients $(|\Gamma| < 0.5)$ the deviation is always less than 0.010 and even around 0.005 below 1000 MHz. This can be explained by the fact that reflection coefficients near the unit circle require a larger dynamic range of the detectors, so nonideal linearization will result in greater errors.

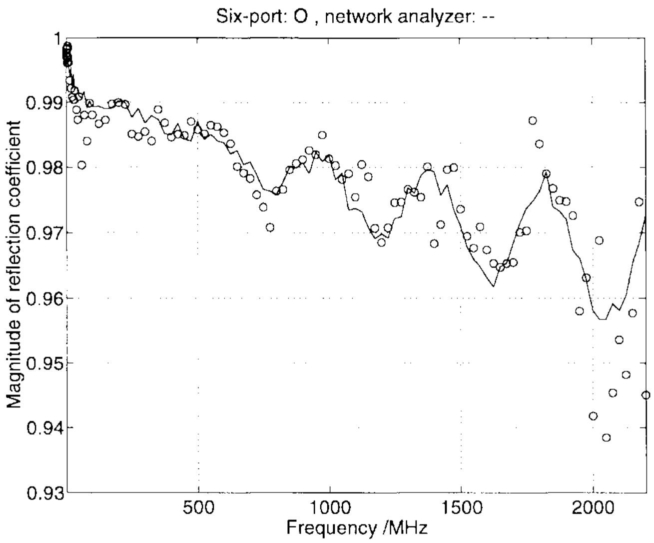

Fig. 8. Magnitude of the reflection coefficient of a test load, measured with the six-port reflectometer shown in Fig. 2 (circles) and a commercial network analyzer (solid line).

V. Conclusion

It has been demonstrated that in combining lumped element reflectors and transmission lines, six-port reflectometers can cover very large bandwidths of three decades. One circuit was designed without a reference detector and showed a performance comparable to the one including a reference detector. As the circuits are built from inexpensive surface mount elements, they are limited to lower frequencies due to their physical dimensions. Hybrid or monolithic technology may shift the operating band to higher frequencies. The implementation of an ac detection scheme will improve the power detection accuracy by suppressing the low frequency flicker noise which occurs in Schottky junctions. The calibration algorithm applied is robust and needs only seven loads to be connected for the complete characterization of the reflectometer over the entire bandwidth.

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