We shall evaluate, as an example, the β_p, γ_p, and γ_o coefficients (associated with the TE mode). Dot multiplying (43) with $\mathrm{grad}_s \psi_p$ and integrating over S gives

$$k_p^2 \beta_p = \int_s \mathrm{curl}\, \mathbf{e} \cdot \mathrm{grad}_s \psi_p dS = \int_s \mathrm{div}(\mathbf{e} \times \mathrm{grad}_s \psi_p) dS - \int_s \mathbf{e} \cdot \mathrm{curl}\, \mathrm{grad}_s \psi_p dS$$

but $\mathrm{curlgrad}_s \psi_p = 0$ and

$$\mathrm{div}\Big(\mathbf{e} \times \mathrm{grad}_s \psi_p\Big) = \mathrm{div}_s\Big(\mathbf{e} \times \mathrm{grad}_s \psi_p\Big) + \frac{\partial}{\partial R} \mathbf{u}_R \cdot \Big(\mathbf{e} \times \mathrm{grad}_s \psi_p\Big).$$

Since

$$\int_s \mathrm{div}_s dS = \int_c (\mathbf{u}_n \cdot \mathbf{a}) dc$$

holds for a tangential vector function $\mathbf{a}(\theta, \varphi)$, we find

$$\beta_p = \frac{\partial v_p}{\partial R} + \frac{1}{k_p^2} \int_c (\mathbf{u}_n \times \mathbf{e}) \cdot \mathrm{grad}_s \psi_p dc.$$

In the next step, we dot multiply (43) with $(1/R)\psi_p$ and $1/R\sqrt{\Omega}$ to obtain after integration

$$\begin{aligned} R\gamma_p &= \int_s (\mathbf{u}_R \cdot \mathrm{curl}\, \mathbf{e}) \psi_p dS \\ &= \int_s \psi_p \mathrm{div}(\mathbf{e} \times \mathbf{u}_R) dS \\ &= \int_s \psi_p \mathrm{div}_s(\mathbf{e} \times \mathbf{u}_R) dS \\ &= \int_s \mathrm{div}_s(\psi_p \mathbf{e} \times \mathbf{u}_R) dS - \int_s \mathrm{grad}_s \psi_p \cdot (\mathbf{e} \times \mathbf{u}_R) dS. \end{aligned}$$

Hence,

$$\gamma_p = \frac{1}{R} \int_c (\mathbf{u}_n \times \mathbf{e}) \cdot \psi_p \mathbf{u}_R dc + k_p^2 v_p.$$

Similarly,

$$\gamma_o = \frac{1}{R\sqrt{\Omega}} \int_c (\mathbf{u}_n \times \mathbf{e}) \cdot \psi_p \mathbf{u}_R dc.$$

Insertion of (43) into Maxwell's equation in $\mathrm{curl}\mathbf{e}$ leads immediately to (18), (20), and (21).

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Six-Port Self-Calibration Based on Active Loads Synthesis

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***Abstract*—An automatic method for self-calibrating six-port reflectometers is reported in this paper. It is based on the use of an active impedance synthesis system. This self-calibration method allows a completely autonomous operation, reduces measurement errors caused by the frequent connecting and disconnecting of calibration standards, and is suitable for low and high frequencies, where sliding shorts are difficult to manufacture. In addition, it simplifies operation of six-port reflectometers to nonspecialized users. The experimented impedance synthesis presented relies on an in-phase and quadrature vector modulator, and the entire system is computer controlled.**

***Index Terms*—Microwave measurement, self-calibration, six-port.**

I. INTRODUCTION

In order to calibrate a six-port reflectometer at a given frequency, many different loads, such as short circuit, matched load, and set of delay lines, have to be connected successively to the measuring port [1]. In theory, 5-1/2 loads are needed to find the junction parameters, but for experimental considerations, the 13 standards method [1] is usually adopted, where 13 unknown different loads have to be connected to the measuring port of the six-port junction.

Thus, automating these procedures requires being able to synthesize many different loads at the measuring port of the six-port junction. Such synthesis can be accomplished using an automated passive impedance tuner systems such as those described in [2] and [3]. However, due to the finite insertion losses, a perfect open or short circuits cannot be obtained, especially at high frequencies. In this paper, we propose a method to avoid such difficulty by using an active loads approach [4], [5]. This method allows synthesis of any load (even outside the unit circle) over the Smith chart for calibration purposes. With this method, all operations that are inherent to the reflectometer such as junction calibration, become invisible to the user, leaving only a simple experimental procedure for error-box measurements [1] to be done, as in standard network analyzers.

II. SYSTEM DESCRIPTION

Six-port reflectometers are usually used for finding the reflection coefficient of a load placed at the measuring port of the six-port junction. Six-port theory [1] shows that this complex coefficient is directly related to the microwave power at each of the four auxiliary ports. By normalizing these quantities with respect to the reference port, we end up with three power ratios that can be used to compute the unknown reflection coefficient.

The block diagram of the system used is shown in Fig. 1. It consists of the six-port reflectometry system (six-port junction, Schottky diode detectors, and CPU) and the controllable vector modulator (or a phase shifter and an attenuator). The incoming signal from the source is split in two parts using a two-way power divider. One of them feeds port 1

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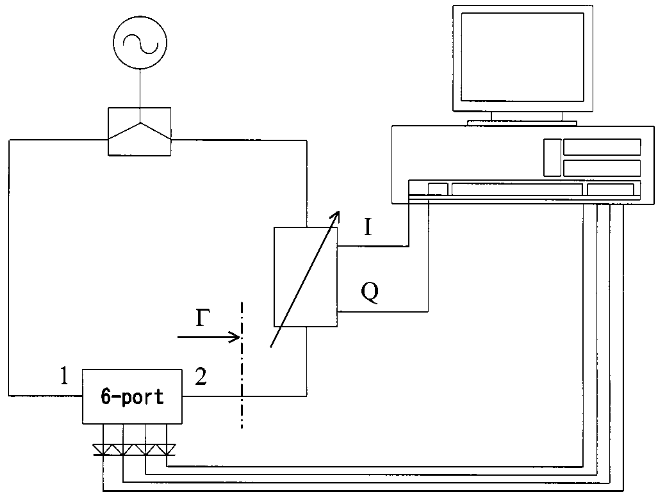

Fig. 1. Block diagram of a self-calibration system for a six-port reflectometer.

of the junction, while the other passes through the modulator and feeds the measuring reference port 2.

With preliminary calibration data, the three measured power ratios are used to compute the value of the reflection coefficient seen at the measuring port [6]. After a comparison with the targeted reflection coefficient, appropriate instructions are sent to the attenuator and phase shifter to correct the coefficient and bring it to the desired value. In this way, the system can produce any reflection coefficient at the measuring port of the junction. Hence, the system is capable of producing successively the different standards needed in practice for a six- to four-port reduction technique [7].

The measurements taken after synthesizing each of the calibration loads constitute new updated calibration data, which can be used to update the previous calibration parameters. A six- to four-port reduction method cannot replace the error box procedure, on which relies the measurements precision, and which is primordial for determining the reference plane [7].

As mentioned above, there is a need for a first manual calibration (e.g., [8], [9]), which can be seen as initial data provided by the system designer or manufacturer. This preliminary data need not to be accurate, as the calibration loads must only be different, regardless of their absolute precise value.

As the system parameters have a small drift in time, due to the numerous possible alterations to the working environment of the junction, (such as temperature variations, detector aging, etc.), this calibration data will grow "old," but can still be used as initial data for self-calibration, knowing that, as mentioned above, its absolute precision is not that important.

An interesting property of the setup that can be stated is its ability to synthesize active loads positioned even outside the unit circle on the Smith chart. Experimentation shows that the measurement precision is excellent in the regions where the calibration loads were situated. This is almost intuitive since interpolation usually gives better precision than extrapolation.

III. The Modulator and its Synthesis Algorithm

The device used to control attenuation and phase shift in the loop is based on an in-phase and quadrature (IQ) vector modulator, which is controlled by two voltages (I and Q) and imposes attenuation and phase shift directly related to these two voltages. This relationship is theoretically described by the following equations:

$$\phi = K \tan^{-1} \frac{I}{Q}$$

and

$$a = K' \sqrt{I^2 + Q^2}$$

where I and Q are the two control voltages, ϕ is the phase shift produced, while a is the attenuation. Thus, if a precise model of this device is available, i.e., if the modulator follows exactly these equations and the constants K and K' are perfectly known, only one iteration measurement procedure is necessary to determine the necessary corrections to the reflection coefficient to bring it to the desired target. If the model is not precise enough, a few number of iterations will be needed to obtain reasonable precision on the targeted reflection coefficient.

As mentioned above, load synthesis may need a certain number of iterations in order to find the proper positions of I and Q to produce the desired reflection coefficient.

A first approximation, i.e., a starting position, is given by the equations above, which place the modulator in a zone nearby the targeted load. At this position (I, Q), four test measurements are made at ($I + \Delta I, Q$), ($I - \Delta I, Q$), ($I, Q + \Delta Q$), and ($I, Q - \Delta Q$) and readings are compared to determine the correction that gives the best results, i.e., that produces the reflection coefficient nearest to the target. The same operation is then repeated at the new position, and so on until the desired precision is attained. If the four test measurements give worse results than the initial position, ΔI and ΔQ are reduced and operation is resumed until the desired precision criteria are met.

IV. Experimental Validation

This automatic self-calibration method was tested between 2–8 GHz on a six-port reflectometer. Calibration measurements obtained were used to calculate p, q, r, a^2, and b^2, which are the parameters that appear in the six- to four-port reduction procedure [1]. These parameters were found to be very close to the ones obtained with conventional calibration methods. Table I presents a comparison between calibration parameters obtained by two consecutive self-calibration procedures and those obtained with a conventional calibration procedure.

These parameters remain very close to each other, which confirms that successive self-calibrations do not deteriorate the measuring system. The slight differences are very easily compensated by the error box so that measurements of a known standard (Table I) remain very precise as self-calibrations are performed.

TABLE I
Six-Port Parameters and Measured Reflection Coefficients of a Known Load Obtained by Manual-Calibration and Self-Calibration Procedures

Calibration					
	p	q	r	a^2	b^2
Manual Calibration	0.1253	0.9844	0.7574	0.1370	0.1802
1st Self-Calibration	0.1379	0.9874	0.7207	0.1096	0.2058
2nd Self-Calibration	0.1306	0.9743	0.7129	0.1075	0.1965

Measurements		
Known Γ	Amplitude: 1.0	Phase: 180
Manual Calibration	0.98	179
1st Self-Calibration	0.99	-179
2nd Self-Calibration	0.98	179

V. Conclusion

An automated method based on active load synthesis for calibrating six-port reflectometers has been proposed and validated. This method provides an interesting alternative for manual calibration, as it is autonomous, independent, and may be much faster. A calibration procedure could be made invisible to the operator, thus allows a much easier operation of a six-port reflectometer to nonspecialized personnel since the only experimental steps that are required are the error-box procedures, as in conventional network analyzers.

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