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RESEARCH ARTICLE

Six-Port Reflectometer Insensitive to Power Detectors' Impedance Mismatch

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ABSTRACT This paper presents the first six-port reflectometer, which is insensitive to power detectors' impedance mismatch. It exhibits optimum measurement conditions and provides low measurement error regardless the reflection coefficient of the used power detectors. Simultaneously, the developed six-port is of low complexity, comparable to other solutions. A theoretical analysis reveals that by application of identical power detectors the impact of their impedance mismatch on the six-port's measurement performance is completely eliminated. To validate this concept experimentally two six-port reflectometers are developed i.e., the proposed one and a reference six-port, which for ideally matched power detectors provides theoretically identical power distribution. Both reflectometers are calibrated and applied to measure reflection coefficients over the frequency range from 5.7 GHz to 5.9 GHz with both well-matched and highly reflective power detectors. The obtained results clearly show that the proposed six-port provides low measurement errors for both types of power detectors, whereas the reference six-port cannot operate properly with highly reflective power detectors.

INDEX TERMS Six-port network, reflectometer, impedance match, power detector, reflection coefficient.

I. INTRODUCTION

Six-port, or more generally multiport reflectometers constitute a group of microwave measurement systems that are based on interferometry. They consist of a multiport power distribution network, to which a signal source and power detectors are connected [1], [2]. In contrast to frequency conversion techniques commonly used nowadays e.g., in vector network analyzers (VNA), they utilize power values measured directly at the frequency of interest, making the circuitry less complex and highly linear at the same time [3], [4]. Due to these advantages six-port (multiport) reflectometers are used in a wide range of wireless application, such as radars [5], receivers for decoding QAM-modulated signals [6], [7], and imaging systems [8]. They are also frequently applied in sensors for material characterization [9], [10], [11]. Frequency range of their operation covers microwaves [12], millimeter waves [13] and optical bandwidth [14].

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To ensure correct operation of a multiport reflectometer, its internal signal distribution must be properly designed. Since the fundamental principle of operation is based on the mentioned interference, two main signals have to be formed i.e., signal proportional to the measured reflection coefficient and a reference signal. Both these have to be combined with different amplitude and/or phase relations and measured by power detectors [15]. This signal formation is the main function of the six-port (multiport) power distribution network, which is a key component of the reflectometer. As reported in [16], this signal distribution scheme, next to the power detectors' measurement uncertainty, is crucial to the resulting reflection coefficient measurement uncertainty of the entire reflectometer. In general, a higher number of power detectors helps to lower the measurement uncertainty. Nevertheless, the overall circuit's complexity increase is a trade-off. Therefore, the most common reflectometers are the six-port ones, as they have the minimum number of three power detectors, that is sufficient to provide a correct measurement. As three ports are used to connect power detectors used for the measurement, the remaining ones serve as feeding port, measurement port to which the measured reflection coefficient is connected, and a port for reference power measurement [17]. To this reference port also a power detector is connected, which however is not directly used in reflection coefficient measurements, as it serves rather to monitor power level delivered from a signal source and/or to make the system's calibration independent on the power level [18].

As indicated above the inner signal distribution is crucial to the obtainable measurement performance. Hence, the power detectors used in a six-port (multiport) reflectometer should exhibit the input reflection coefficient as low as possible, as signals reflected from them deteriorate the inner signal distribution, which as mentioned above is crucial to the reflection coefficient measurement uncertainty [16]. It is well-known that diode power detectors inherently exhibit a poor impedance match and need a dedicated impedance matching network [19], [20]. Their application requires a distinct area, since it must be added for each power detector. Moreover, a design of impedance matching network for a diode power detector that would provide a good impedance match over a wide frequency range can be particularly difficult [21].

This problem has been partially overcome in [22], where a six-port reflectometer incorporating four non-matched power detectors is proposed. It makes use of the signals reflected from the reflective power detectors to form the reference signal necessary for the above-mentioned interference being the fundamental principle of multiport reflectometers' operation. However, this solution suffers from a direct dependence between the power detectors' reflection coefficient and the power distribution of the six-port network. Therefore, the measurement uncertainty for such a reflectometer also depends on the connected power detectors.

In this paper for the first time a novel six-port reflectometer is presented, in which the signal distribution scheme does not depend on the power detectors' impedance match level. Therefore, the same measurement performance can be obtained for power detectors, which are well-matched or they exhibit even distinct reflectivity. Such a feature has never been reported up to date, as performance of other six-port reflectometers becomes strongly impaired when highly reflective power detectors are used. Moreover, the signal distribution provided by the proposed six-port network is optimum with respect to the measurement uncertainty for all reflection coefficients of magnitude not exceeding unity. The presented concept is theoretically analyzed. It is shown that by utilizing four identical power detectors, the unwanted signals reflected from power detectors in the proposed reflectometer become completely suppressed. For an experimental confirmation two reflectometers are developed: the proposed one and a reference one, which for ideally matched power detectors exhibits theoretically identical signal distribution scheme. Both reflectometers are designed, fabricated, calibrated, and used to measure complex reflection coefficients over the bandwidth from 5.7 GHz to 5.9 GHz. The calibration and measurements are done for each reflectometer twice. First, with well-matched power detectors, and the second time with highly reflective ones. It is shown that the proposed six-port reflectometer exhibits optimum parameters and low measurement errors for both types of power detectors. In contrast, the reference six-port reflectometer's performance significantly worsens when the power detectors are not matched.

II. THEORETICAL ANALYSIS

A schematic diagram of the proposed six-port reflectometer is presented in Fig. 1. As seen it is composed of 3 × 3 Butler matrix, two quadrature directional couplers Q_1 and Q_2, and three sections of matched transmission line TL_1, TL_2, and TL_3. All these components constitute a six-port power distribution network fed at port #1, and device under test (DUT), the reflection coefficient Γ of which is to be measured is connected to port #2. To all remaining ports #3 – #6 of the six-port network four identical power detectors are connected, which exhibit input reflection coefficient Γ_D.

As discussed above, in majority of six-port reflectometers, signals reflected from power detectors interfere with the desired signal distribution in the reflectometer, which manifests itself in impaired measurement uncertainty. However, in the proposed six-port reflectometer, impact of these unwanted signals can be suppressed by directing them to match loads terminating port #2 of the 3 × 3 Butler matrix and port #2 of the coupler Q_2. To illustrate this, the following analysis can be conducted. Assuming that the couplers Q_1^{BM} and Q_3^{BM} are directional couplers with power division ratio 1:1 and the coupler Q_2^{BM} realized power division ratio 2:1 i.e.:

$$\left|S_{41}^{Q_1^{BM}}\right| = \left|S_{31}^{Q_1^{BM}}\right| = \left|S_{41}^{Q_3^{BM}}\right| = \left|S_{31}^{Q_3^{BM}}\right| \tag{1}$$

$$\left|S_{41}^{Q_2}\right| = \sqrt{2}\left|S_{31}^{Q_2}\right| \tag{2}$$

and the electrical lengths of the transmission lines TL_1^{BM} and TL_4^{BM} are equal to 90°, whereas the electrical lengths of the transmission lines TL_2^{BM}, TL_3^{BM}, and TL_5^{BM} are equal to 180° at the center frequency of operation, these components form an ideal 3 × 3 Butler matrix, which can be described by the following S-matrix:

$$S^{BM} = \frac{1}{\sqrt{3}}\begin{bmatrix} 0 & 0 & 0 & e^{j\frac{5\pi}{6}} & e^{j\frac{\pi}{6}} & e^{-j\frac{\pi}{2}} \\ 0 & 0 & 0 & e^{j\frac{\pi}{6}} & e^{j\frac{5\pi}{6}} & e^{-j\frac{\pi}{2}} \\ 0 & 0 & 0 & e^{-j\frac{\pi}{2}} & e^{-j\frac{\pi}{2}} & e^{-j\frac{\pi}{2}} \\ e^{j\frac{5\pi}{6}} & e^{j\frac{\pi}{6}} & e^{-j\frac{\pi}{2}} & 0 & 0 & 0 \\ e^{j\frac{\pi}{6}} & e^{j\frac{5\pi}{6}} & e^{-j\frac{\pi}{2}} & 0 & 0 & 0 \\ e^{-j\frac{\pi}{2}} & e^{-j\frac{\pi}{2}} & e^{-j\frac{\pi}{2}} & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

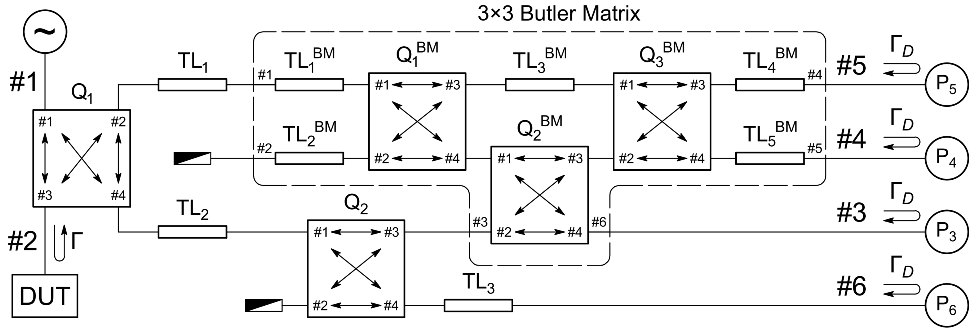


FIGURE 1. A schematic diagram of the proposed six-port reflectometer insensitive to power detectors' impedance mismatch.

As it is shown in Fig. 1, three identical power detectors having the reflection coefficient Γ_D are connected to all output ports of the 3×3 Butler matrix. The scattering matrix of such connection is equal to:

$$S^{BM+\Gamma_D} = \begin{bmatrix} 0 & -\Gamma_D & 0 \\ -\Gamma_D & 0 & 0 \\ 0 & 0 & -\Gamma_D \end{bmatrix} \tag{4}$$

To enable measurement with a six-port reflectometer in general, it is required that three power detectors $P_3 - P_5$ measure the power of a sum of two signals, among which the first one is a signal depending on the measured reflection coefficient Γ, whereas the second one is Γ-independent and serves as a reference. Analyzing the schematic diagram and (4) it can be observed, that the first signal is delivered from the signal source, propagates through the coupler Q_1, reflects from DUT (proportionally to its reflection coefficient Γ), propagates through the coupler Q_1 again and through the line TL_1, and incidents to port #1 of the Butler matrix with no reflection and further to power detectors $P_3 – P_5$. As given in (4), the signal reflected from power detectors is directed to port #2 of the Butler matrix, which is terminated with a matched load.

The second (reference) signal propagates from the signal source through the coupler Q_1 and the line TL_2. Further, it is delivered to port #1 of the coupler Q_2. As given in (4), the reflection coefficient seen from port #3 of the coupler Q_2 is equal to $–\Gamma_D$. Hence, to obtain the reflection coefficient seen at port #1 of the coupler Q_2 equal to 0, also the reflection coefficient equal to $–\Gamma_D$ should be seen at port #4 of the coupler Q_2. This can easily be done by connecting the power detector P_6 to port #4 of the coupler Q_2 through the transmission line TL_3 having the electrical length of 90°. It transforms the reflection coefficient seen from port #4 of the coupler Q_2 to the same one seen at port #3 of that coupler. Hence, due to quadrature of the coupler Q_2, the reflection coefficient seen at port #1 of the coupler Q_2 is equal to 0 and the reflected power is directed to the match load connected to port #2 of the coupler Q_2.

As explained above, both analyzed signals are delivered to the Butler matrix and the coupler Q_2 with no reflections,

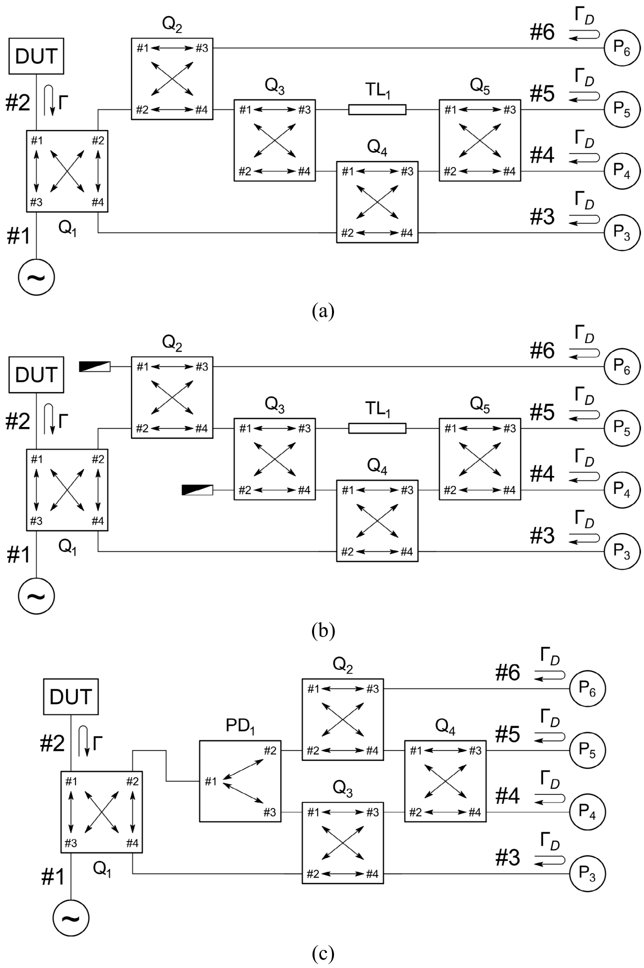


FIGURE 2. Schematic diagrams of exemplary six-port reflectometers for comparison of the immunity to power detectors' impedance mismatch: (a) reference six-port [23], (b) reference six-port [23] with terminations connected to unused ports of internal couplers Q_2 and Q_3, and (c) the classic six-port [24].

hence the reflection coefficient of power detectors Γ_D has no influence on the power distribution scheme, which is crucial to obtainable reflection coefficient measurement uncertainty [16]. On the other hand, a higher reflection coefficient Γ_D leads to a decrease of power efficiently measured by power

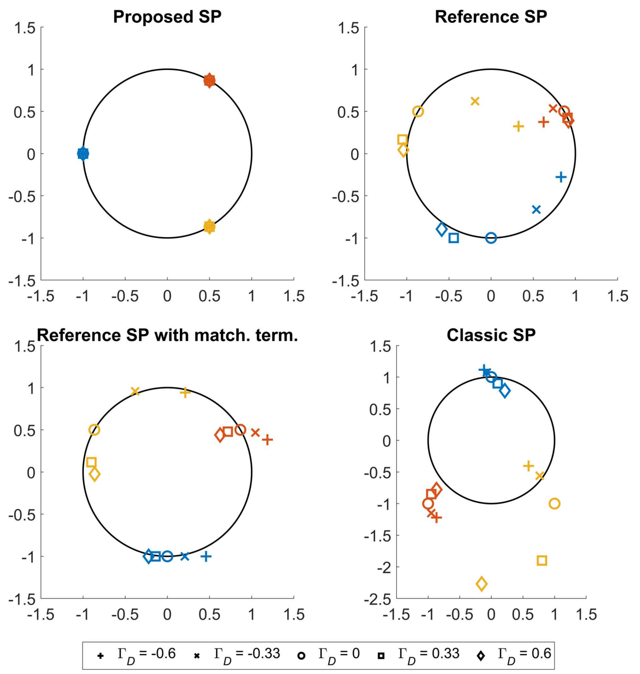


FIGURE 3. **Comparison of the circle centers' distributions of the proposed six-port and other six-ports reported in literature for different reflection coefficient of the power detectors Γ_D.**

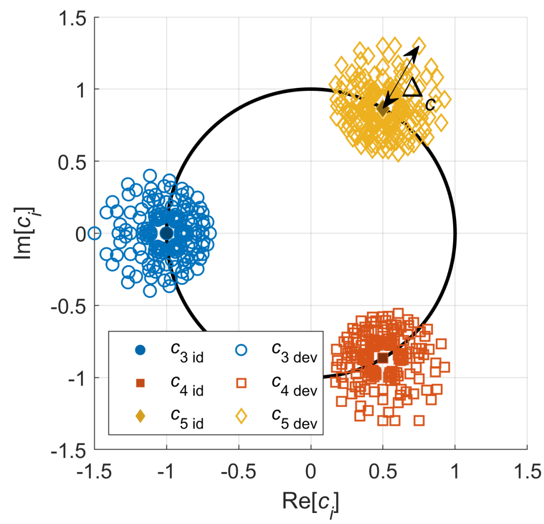


FIGURE 4. **Set of 1296 circle centers' distributions obtained by deviating the power detectors' reflection coefficients Γ_{Di} by $\delta = 0.25$ with uncorrelated deviation of phases from 0° to 360° with 60°-steps.**

detectors (accepted power). However, as shown in [22] modern power detectors exhibit power dynamics ranges wider than it is required in six-port reflectometers. Therefore, even a distinct impedance mismatch can be acceptable in the proposed six-port reflectometer. The power measured by the power meters is equal to

$$P_3 = P_{GEN}\left(1-|\Gamma_D|^2\right)\cdot\left|S_{31}^{Q_1}\Gamma S_{23}^{Q_1}E_1S_{61}^{BM}+S_{41}^{Q_1}E_2S_{31}^{Q_2}S_{63}^{BM}\right|^2 \tag{5}$$

$$P_4 = P_{GEN}\left(1-|\Gamma_D|^2\right)\cdot\left|S_{31}^{Q_1}\Gamma S_{23}^{Q_1}E_1S_{51}^{BM}+S_{41}^{Q_1}E_2S_{31}^{Q_2}S_{53}^{BM}\right|^2 \tag{6}$$

$$P_5 = P_{GEN}\left(1-|\Gamma_D|^2\right)\cdot\left|S_{31}^{Q_1}\Gamma S_{23}^{Q_1}E_1S_{41}^{BM}+S_{41}^{Q_1}E_2S_{31}^{Q_2}S_{43}^{BM}\right|^2 \tag{7}$$

$$P_6 = P_{GEN}\left(1-|\Gamma_D|^2\right)\cdot\left|S_{41}^{Q_1}E_2S_{41}^{Q_2}E_3\right|^2 \tag{8}$$

where P_{GEN} is power delivered by the signal source connected to port #1 of the six-port network and E_k is the transmission coefficient of ideally matched transmission line TL_k ($k = 1, 2, 3$). Thus, (5)-(7) can be expressed by the well-known general formula used for all six-port reflectometers i.e.:

$$P_i = q_i\left|1 + A_i\Gamma\right|^2 \tag{9}$$

where $i = 3, 4, 5$, and

$$q_i = P_{GEN}\left(1-|\Gamma_D|^2\right)\cdot\left|S_{41}^{Q_1}E_2S_{31}^{Q_2}S_{9-i,3}^{BM}\right|^2 \tag{10}$$

$$A_i = \frac{S_{31}^{Q_1}S_{23}^{Q_1}E_1S_{9-i,1}^{BM}}{S_{41}^{Q_1}E_2S_{31}^{Q_2}S_{9-i,3}^{BM}} \tag{11}$$

Assuming that the couplers Q_1 and Q_2 exhibit power division ratio 1:1, (10) and (11) can be simplified to the following:

$$q_i = \frac{1}{12}P_{GEN}\left(1-|\Gamma_D|^2\right) \tag{12}$$

$$A_i = \frac{E_1S_{9-i,1}^{BM}}{E_2S_{9-i,3}^{BM}} \tag{13}$$

Furthermore:

$$P_6 = \frac{1}{4}P_{GEN}\left(1-|\Gamma_D|^2\right) \tag{14}$$

Equation (9) is the well-established relation between the reflection coefficient Γ being the subject to measure and the measured power P_i [1], [16]. It represents three circles on a complex plane, which have a single intersection point being the reflection coefficient Γ. These circles have their centers c_i located at:

$$c_i = -\frac{1}{A_i} \tag{15}$$

and their radii are proportional to the measured power P_i:

$$r_i = \sqrt{\frac{P_i}{q_i\,|A_i|^2}} \tag{16}$$

Mutual arrangement of c_i points on the complex plane is crucial as it, together with the power measurement uncertainty, defines the reflection coefficient measurement uncertainty. As seen in (11) and (13), the proposed six-port reflectometer exhibits the circle centers' distribution which does not depend on the power detectors' reflection coefficient Γ_D, which is not achievable for other reported solutions. Furthermore, by analyzing (13) it can be stated that the

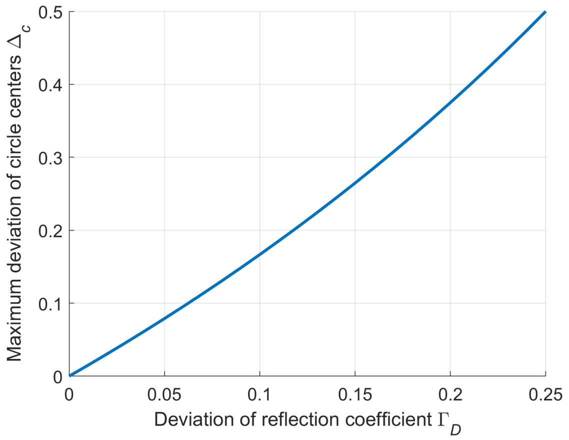


FIGURE 5. **Maximum deviation of circle centers Δ_c vs. the deviation of the power detectors' reflection coefficients.**

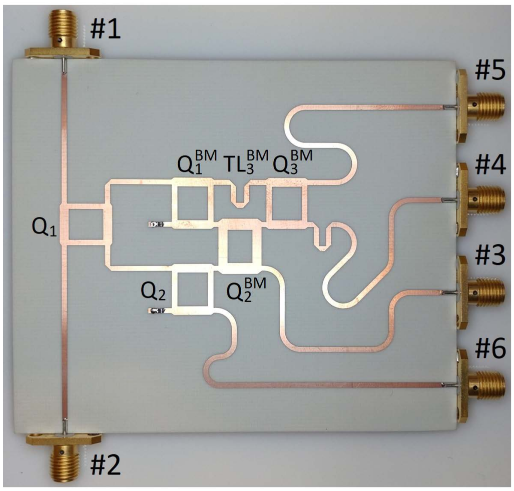


FIGURE 6. **A photograph of the fabricated proposed six-port reflectometer.**

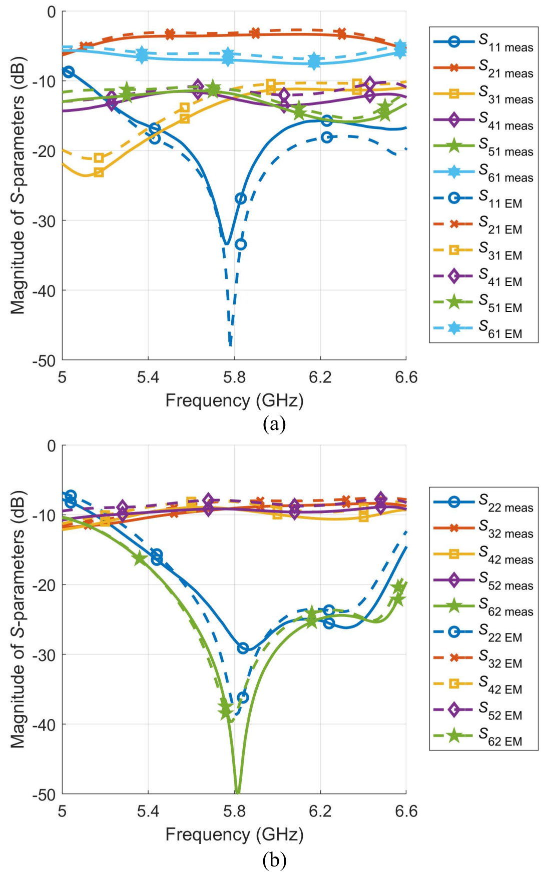


FIGURE 7. **Scattering parameters of the designed six-port network: (a) coincident with port #1 and (b) coincident with port #2.**

mutual arrangement does not depend on the electrical length TL_1 and TL_2, as their values only rotates all three c_i points simultaneously, preserving their mutual arrangement, which has no influence on the overall measurement uncertainty. Assuming identical electrical lengths of the lines TL_1 and TL_2 ($E_1 = E_2$), the circle centers' distribution is equal to:

$$c_3 = -1 \tag{17}$$

$$c_4 = e^{-j\frac{\pi}{3}} \tag{18}$$

$$c_5 = e^{j\frac{\pi}{3}} \tag{19}$$

which is considered to be the optimum one, if all reflection coefficients having the magnitudes not exceeding unity ($|\Gamma| \leq 1$) are taken into account [16].

III. COMPARISON OF THE IMPACT OF POWER DETECTORS' MISMATCH ON SIX-PORT REFLECTOMETERS

In the previous section it is shown that the proposed six-port is insensitive to impedance mismatch of the utilized power detectors. As discussed above, this advantage makes it exceptional among other reported solutions. To demonstrate this, the following three six-port reflectometers have been chosen for comparison against the proposed one.

The first one is a six-port reported in [23], called further reference six-port (or RSP), as it provides nearly identical circle centers' distribution to the one of the proposed six-port. The only difference is a rotation by 90°, which has no impact on the measurement performance. Its schematic diagram is shown in Fig. 2(a). As seen it is composed of five directional couplers $Q_1 - Q_5$, hence the network complexity is comparable (or same) to the proposed one.

As can be observed the reference six-port contains two directional couplers with single ports left open i.e., port #1 of the coupler Q_2 and port #2 of the coupler Q_3. It should be underlined that in a proper operation with no reflections from matched power detectors, these ports do not receive any signals, hence they do not need to be terminated with a matched load. However, in the considered case, when the power detectors can have arbitrary reflection coefficient Γ_D, these ports obviously will introduce additional reflections, which will deteriorate the inner signal flow, and thus the obtainable circle centers' distribution. To eliminate this effect, these two ports have been terminated with an ideally matched load. Such

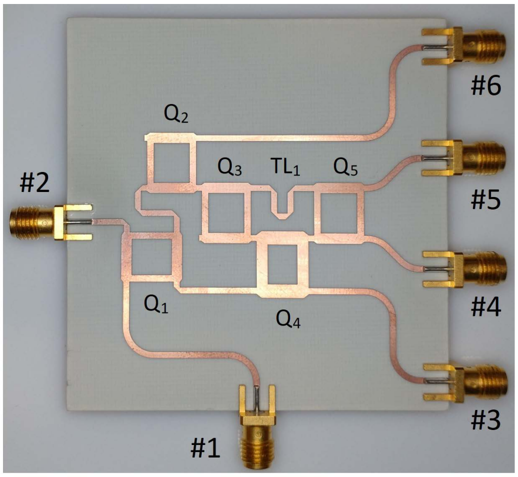


FIGURE 8. A photograph of the fabricated reference six-port reflectometer.

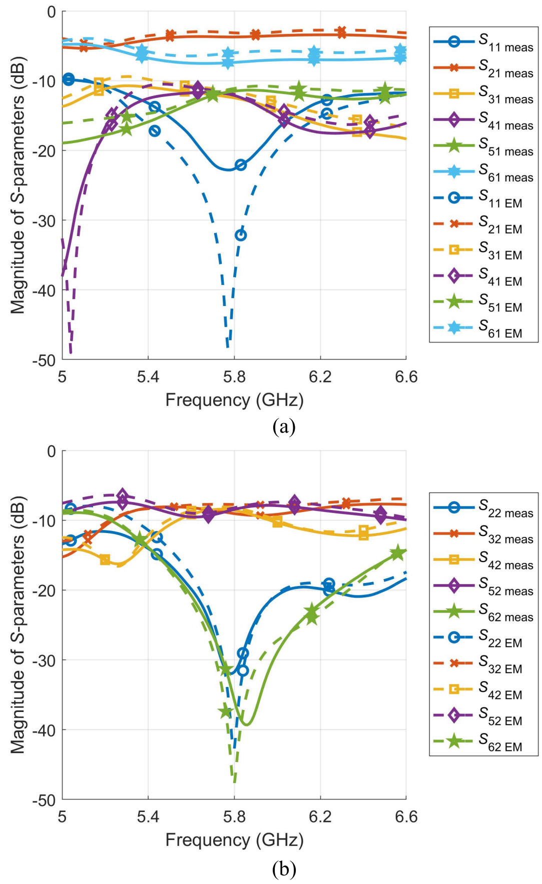


FIGURE 9. Scattering parameters of the designed reference six-port network: (a) coincident with port #1 and (b) coincident with port #2.

configuration, called further reference six-port with matched terminations, is illustrated in Fig. 2(b).

The last six-port selected for comparison is the structure reported in [24], called further the classic six-port. It is a six-port closely corresponding to the original early works in six-port technique [1], [15], [17] seen in Fig. 2(c). It exhibits a different circle centers' distribution, composed of three points having magnitudes equal to 1, $\sqrt{2}$, and $\sqrt{2}$, whereas their angular separation equals 135°, 90°, and 135°, respectively. It is composed of four directional couplers $Q_1 - Q_4$ and a power divider PD_1, hence again, the network complexity is similar to all considered six-ports.

For all the above six-ports a circuit simulation with power detectors having variable input impedance was performed at the center frequency of operation. The mentioned input impedance of the power detectors was set to be $0.25Z_0$, $0.5Z_0$, Z_0, $2Z_0$, and $4Z_0$, which corresponds to the reflection coefficients Γ_D equal to -0.6, -0.33, 0, 0.33, and 0.6, respectively. The obtained circle centers' distributions are presented in Fig. 3. As seen only the proposed six-port is not affected by power detectors' reflection coefficient Γ_D, which clearly corresponds to the theoretical predictions given in Section II. All the other six-ports strongly deteriorate, when non-matched power detectors are applied. It is seen that the reference six-port becomes significantly impaired for reflective power detectors, which could be justified by the lack of terminations at two unused ports, as discussed above. However, it is seen that circle centers' distribution of the reference six-port with matched terminations deteriorates as well, although not as strongly as in the previous case. It is therefore seen that the impairment of the circle centers' distribution of the reference six-port does not only results from the lack of these terminations, but also from the internal signal flow which requires no reflections from power detectors.

The last six-port, namely the classic six-port, exhibits the highest sensitivity to the power detectors' reflection coefficient Γ_D. Moreover, even with ideally matched power detectors, it provides circle centers' distribution which leads to worse measurement uncertainty than the one obtainable for the proposed and reference six-ports [16]. Hence, it can be stated that the proposed six-port as the only one provides the optimum circle centers' distribution, which simultaneously does not change whether the power detectors are matched or they exhibit even large reflection.

IV. SENSITIVITY TO DISCREPANCY OF POWER DETECTORS' REFLECTION COEFFICIENTS

The above analysis shows that the proposed six-port can optimally operate regardless the value of power detectors' reflection coefficient as long as all the power detectors exhibit the same reflection coefficient Γ_D. However, in practice some discrepancy between their reflection coefficients is expected due to production spread and manufacturing tolerances. To complete the analysis, a sensitivity of circle centers' distribution of the proposed six-port to discrepancy of the power detectors' reflection coefficients needs to be verified.

For this purpose, the nominal values of the power detectors' reflection coefficients Γ_D were deviated by a complex value having fixed magnitude δ and phase varying in full 360°-range. Hence, the reflections seen at ports i-th ports

($i = 3, \ldots, 6$) of the six-port reflectometer take the values:

$$\Gamma_{Di} = \Gamma_D + \delta \cdot e^{j\phi_i} \tag{20}$$

where δ is real and common for all power detectors P_3 – P_6, whereas the phases φ_i are arbitrary and not corelated. For such a set of four non-identical reflection coefficients Γ_{Di} the corresponding circle centers' distribution of the proposed six-port reflectometer can be calculated. Fig. 4 presents results obtained for the nominal value of reflection coefficient $\Gamma_D = 0$, and for relatively large deviation δ equal to 0.25. The phases φ_i cover full 360° with 60° steps, which gives $6^4 = 1296$ solutions (six values of phase φ_i independently chosen for four power detectors). As seen the deviation of particular power detectors' reflection coefficients Γ_{Di} by relatively large value $\delta = 0.25$ leads to a visible deviation of circle centers' distribution, which however, is not significant. The maximum deviation Δ_c for each circle takes the same value of 0.5. It must be underlined that for each of 1296 circle centers' distributions seen in Fig. 4 a precise reflection coefficient measurement is possible.

Further analysis reveals that the obtained maximum deviation of the circle centers' distribution Δ_c does not depend on the nominal value Γ_D. Therefore, the procedure described above can be easily extend on a wider range of δ, and the obtained values will be valid for arbitrary value of Γ_D. Fig. 5 presents the maximum obtainable deviation of circle centers Δ_c vs. deviation of the power detectors' reflection coefficient Γ_D swept over the range from 0 to 0.25. This relation can be approximated by the following quadratic formula:

$$\Delta_c = 2.282\delta^2 + 1.415\delta + 0.002 \tag{21}$$

with the error lower than 0.002. As seen the proposed six-port reflectometer does not require four identical power detectors and some discrepancy between them is permissible.

The sensitivity of the proposed six-port reflectometer can be illustrated with the following manner. Assuming the maximum acceptable deterioration of circle centers equal to $\Delta_c = 0.5$, the deviation of power detectors' reflection coefficients should not exceed the value of $\delta = 0.25$. This can be achieved e.g., in two ways. Firstly, it is obtained if all power detectors exhibit the magnitudes of reflection coefficient not exceeding -12 dB ($|\Gamma_{Di}| \leq 0.25$). Then the phases of the power detectors' reflection coefficients can be arbitrary, as for such a case all the reflection coefficients Γ_{Di} are at the distance not higher than 0.25 from $\Gamma_D = 0$. Secondly, assuming exemplary value of $\Gamma_D = 0.5$ the same deviation of circle centers Δ_c can be obtained if the all reflection coefficients Γ_{Di} share the same phase and their magnitudes fall within the range from -12 dB to -2.5 dB (from 0.25 to 0.75). It is therefore seen that the proposed six-port reflectometer does not require identical reflection coefficients of the used power detectors, and even distinct discrepancy between them is allowed.

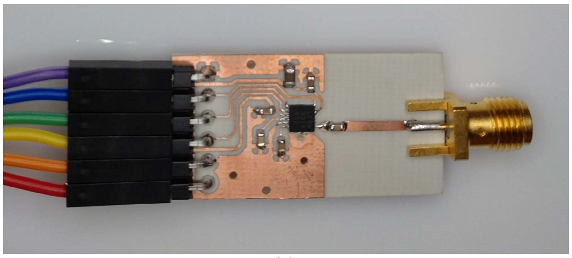
V. DESIGN OF THE PROPOSED SIX-PORT REFLECTOMETER

For experimental verification the proposed six-port reflectometer was designed in microstrip structure using RO4003C laminate by *Rogers*. Its thickness is equal to 0.508 mm and its relative permittivity equals 3.55. The center frequency was selected to 5.8 GHz, which results from the choice of power detectors designated to use in conjunction with the developed six-port network, as it will be further described in this paper. The six-port network was designed using *AWR Design Environment* by *Cadence*. The directional couplers were designed as the classic branchline couplers, and the matched loads were realized as parallel connections of two 100-Ω 0402 SMD resistors connected to ground plane through a via. Additionally, to obtain a spacing between SMA connectors necessary to connect the power detectors P_3 – P_6 through SMA connectors, the transmission lines at ports #3 – #6 were extended by identical length and appropriately meandered.

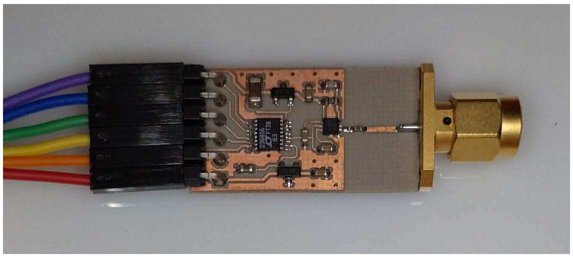
A photograph of the fabricated proposed six-port network is illustrated in Fig. 6. Its measured scattering parameters vs. the ones obtained in electromagnetic simulation are depicted in Fig. 7. As can be observed the developed six-port network exhibits a very good impedance match at the feeding port #1 and the measurement port #2. Simultaneously, all transmission coefficients from the feeding port #1 to ports with power detectors #3 – #5 are of equal magnitudes and the same can be observed for the transmission coefficients from the measurement port #2 to ports with power detectors #3 – #5, which is necessary to obtain equal magnitudes of circle centers c_i. Additionally, a high isolation between the port #6 serving for reference power measurement and the measurement port #2 exists. A slight discrepancy between the measured and EM calculated results is due to SMA connectors soldered in the fabricated six-port, the parameters of which were neglected in EM simulation, as well as due to fabrication intolerances.

VI. DESIGN OF THE REFERENCE SIX-PORT REFLECTOMETER

To experimentally confirm the advantageous immunity of the proposed six-port reflectometer to the power detectors' impedance mismatch over other reported solutions, the reference six-port reported in [23] has also been developed. As described earlier, it exhibits theoretically identical circle centers' distribution and comparable topology, however, for a proper operation it requires that all power detectors must be well-matched. It was designed using the same substrate as the proposed six-port i.e., RO4003C laminate by *Rogers*. Its center frequency of operation is also equal to 5.8 GHz. A photograph showing the fabricated reference six-port network is presented in Fig. 8, whereas its scattering parameters are plotted in Fig. 9. It is seen that the power distribution scheme is similar to the one obtained for the proposed six-port network. Hence, it should also provide circle centers' distribution with c_i points of equal magnitudes, which however can only be obtained for well-match power detectors.



(a)



(b)

FIGURE 10. Photographs of the power detectors incorporated in the developed reflectometer setups: (a) highly reflective power detector LTC5587 with the reflection coefficient Γ_R and (b) well-matched power detector LTC5597 with small reflection coefficient Γ_M.

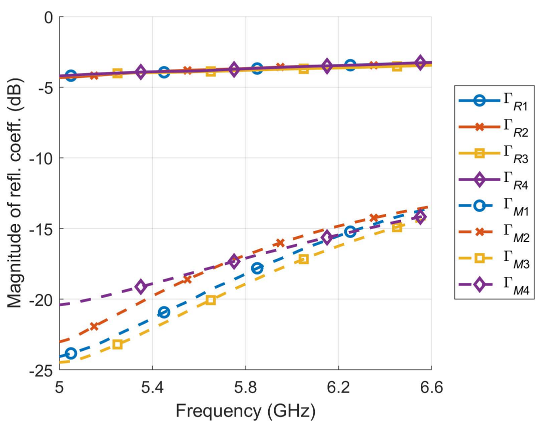


FIGURE 11. Measured reflection coefficients of four fabricated highly reflective power detector LTC5587 with the reflection coefficient Γ_R and four fabricated well-matched power detector LTC5597 with low reflection coefficient Γ_M.

This crucial difference between these two six-port networks will be revealed further in the next section.

VII. DEVELOPMENT AND CALIBRATION OF THE MEASUREMENT SETUP

The two fabricated six-port networks were incorporated in a reflectometer setup, namely: reflectometer with the proposed six-port (PSP) and reflectometer with the reference six-port (RSP). For both configurations SMB 100A signal source by *Rohde&Schwarz* was used as the excitation connected to port #1 of the six-port network.

To comprehensively verify the insensitivity of PSP to power detectors' mismatch, which does not occur for RSP two different types of power detectors need to be selected i.e., highly reflective power detectors with the reflection coefficient Γ_R and well-matched power detectors with a low reflection coefficient Γ_M. As the reflective detectors four LTC5587 RF power detectors by *Analog Devices* were selected. At their maximum frequency of operation specified by the producer, being equal to 5.8 GHz, they exhibit the reflection coefficient around -3 dB and the power measurement dynamic range from -25 dBm to 0 dBm with ± 0.3 dB of the nonlinearity error. As the second type of power detectors LTC5597 RF power detectors were chosen. They are equipped with internal matching network which according to specification, ensures their input reflection coefficient to be around -15 dB at 5.8 GHz. At this frequency their provide power measurement within the range from -35 dBm to 0 dBm with the nonlinearity error of ± 0.3 dB.

To make the measurement automatic a dedicated data acquisition module was developed. It utilizes ZYBO Z7-20 FPGA board by *Digilent*, which constitutes an interface between PC and the detectors. Since LTC5587 power detectors are equipped with an internal 12-bit A/D converters, the FPGA boards communicates directly with these detectors via 3-wire serial interface. The developed communication block allows for simultaneous triggering and read-out of all power detectors with the maximum rate of 500 kHz, which is limited by the power detectors' specification. Similar communication block was implemented in the FPGA board for the second type of power detectors, i.e., LTC5597, however, with one distinct difference. These detectors do not contain built-in A/D converters, therefore an external chip was needed. For this purpose, a 16-bit LTC2368-16 A/D converter was chosen. It uses 4-wire serial communication, and enables sampling with the rate up to 1 MS/s. Also in this case, simultaneous triggering and read-out is ensured.

Since both PSP and RSP require four power detectors, four identical detectors were fabricated for each of the group. Photographs of the fabricated detectors are illustrated in Fig. 10. Moreover, their measured reflection coefficients are shown in Fig. 11. A large difference in impedance matching between both groups of detectors is clearly seen. Simultaneously, within each group the reflection coefficients are consistent to each other. Hence, for the chosen frequency of 5.8 GHz the two groups of detectors exhibit a good dynamic range, comparable nonlinearity errors and significant difference in the reflection coefficient, which makes them suitable to verify the impact of the power detectors' reflection coefficient on the performance of PSP and RSP. Due to this reason the center frequency of both reflectometers should also be equal to 5.8 GHz.

Having all the described components the measurement setup can be formed in four configurations:

a) Reflectometer with the proposed six-port network and well-matched power detectors PSP + Γ_M,
b) Reflectometer with the proposed six-port network and highly reflective power detectors PSP + Γ_R,
c) Reflectometer with the reference six-port network and well-matched power detectors RSP + Γ_M,

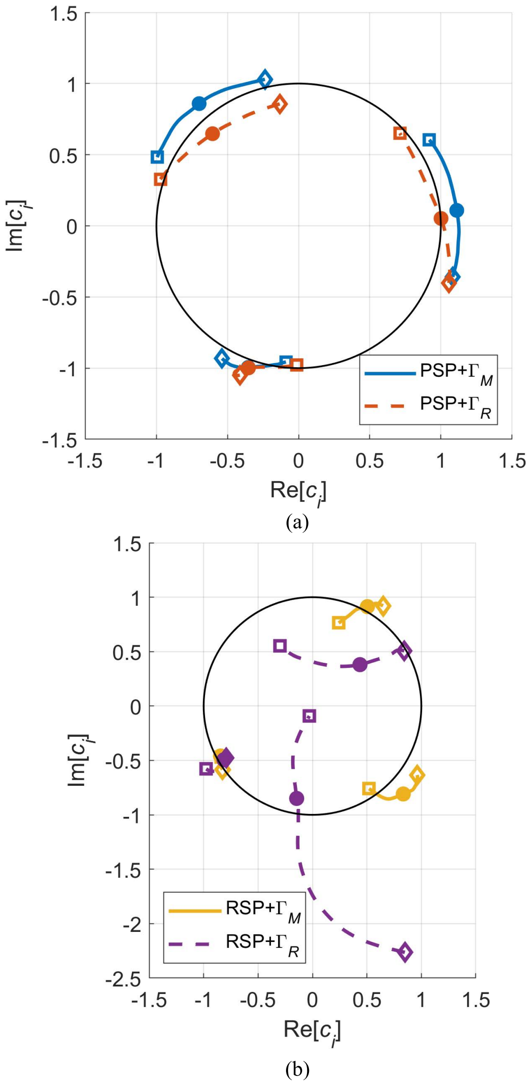


FIGURE 12. **Circle centers' distributions obtained in calibration of the developed reflectometers with well-matched power detectors (Γ_M) and with highly reflective power detectors (Γ_R): (a) reflectometer with the proposed six-port network (PSP) and (b) reflectometer with the reference six-port network (RSP). Markers indicate the following frequencies: ◇ – 5.7 GHz, • – 5.8 GHz, and □ – 5.9 GHz.**

d) Reflectometer with the reference six-port network and highly reflective power detectors RSP + Γ_R.

Each of the above configuration was calibrated over the frequency range from 5.7 GHz to 5.9 GHz following the procedure described in [25]. It is based on the measurement of a set of one-port calibration standards having known reflection coefficients, which are: matched load and open- and short-circuit with additional phase shifters. This procedure allows for an extension of the model given by (9) into the form:

$$P_i = q_i \left| \frac{1 + A_i\Gamma}{1 + A_0\Gamma} \right|^2 \tag{22}$$

where parameter A_0 represents the non-ideal impedance match of the measurement port and finite isolation S_{62} of the six-port network.

To visually assess the calibration results for all four configurations it is convenient to represent them in a form of circle centers' distribution. As discussed above, both PSP and RSP ideally exhibit circle centers c_i that form an equilateral triangle and the magnitude of c_i should be equal to 1. In Fig. 12 a comparison of the four circle centers' distributions is provided. It is seen that the circle centers' distribution obtained for PSP fully meets the theoretical expectations and is almost independent on the power detectors' impedance match level. Only a slight difference between the results for PSP $+\Gamma_M$ and PSP $+\Gamma_R$ exists, which is due to imperfect impedance match of the matched loads realized using SMD resistors and vias, as well as due to not identical reflection coefficients of all power detectors. Nevertheless, for each considered frequency, the circle centers c_i form a triangle close to equilateral one as expected, and their simultaneous rotation has no impact on the overall measurement uncertainty.

In contrast, circle centers' distribution obtained for RSP exhibits a high sensitivity to the power detectors' impedance mismatch. As seen, if well-matched power detectors are used (RSP + Γ_M) the mutual arrangement of c_i points is similar to the one obtained for PSP, however, it drastically deteriorates if power detectors become reflective (RSP + Γ_R). This will lead to a significant increase of the reflection coefficient measurement error.

VIII. MEASUREMENTS OF REFLECTION COEFFICIENT

To complete the experimental verification the developed reflectometers were used to measure complex reflection coefficients over the bandwidth of calibration i.e., from 5.7 GHz to 5.9 GHz. To cover a wide range of the measured reflection coefficient's magnitude a set of broadband SMA attenuators terminated with a short-circuit was chosen. Attenuation of the selected attenuators is equal to 1 dB, 2 dB, 3 dB, 6 B, and 10 dB, which correspond to the measured reflection coefficient's magnitudes varying from −2 dB to −20 dB. The measurements were performed for all four configurations described in the previous section. Additionally, a vector network analyzer (VNA) N5224A by *Keysight* was used for reference measurements. The obtained results are shown in Fig. 13 and Fig. 14. Due to similar phase characteristics of all measured reflection coefficients, in Fig. 14 only the phase measured for the highest and for the lowest magnitudes are shown.

The measurement results clearly show the advantage of the proposed six-port (PSP) network over the reference one (RSP). It is seen that PSP allows for precise measurements regardless the power detectors' matching level. It is a consequence of the stable circle centers' distribution seen in Fig. 12(a), which does not deteriorate for an impedance mismatch of the power detectors. On the other hand, RSP is only capable of correct measurement if well-matched power detectors are used. For such a case, the measurement error is

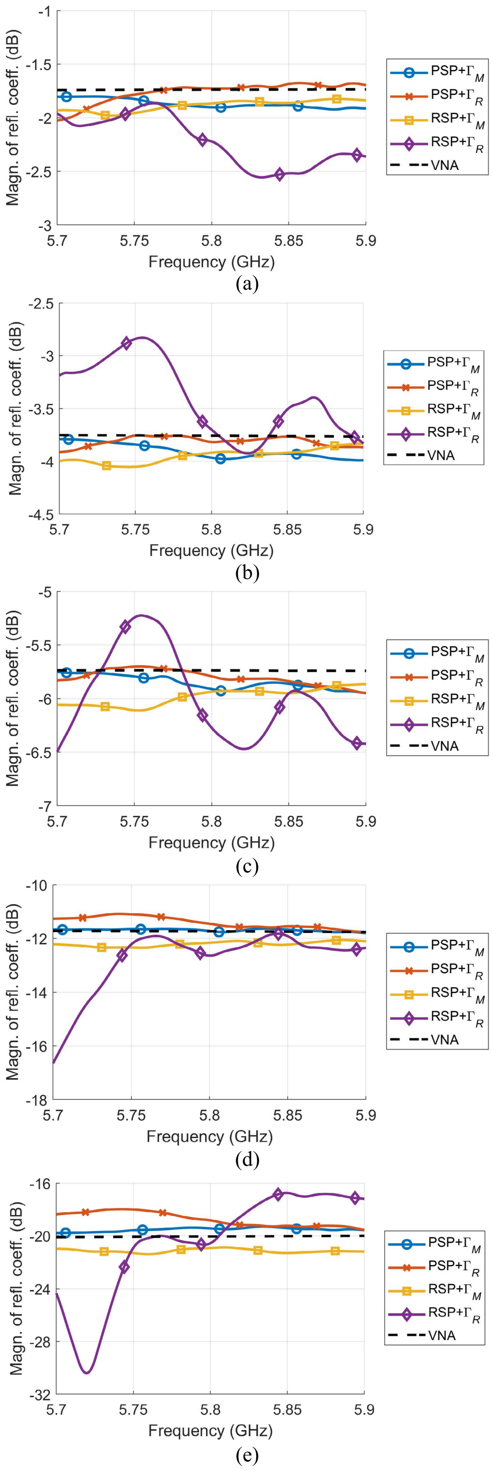


FIGURE 13. **Magnitude of reflection coefficients of attenuators terminated with a short-circuit measured using reflectometer with the proposed (PSP) and the reference (RSP) six-port network, with well-matched (Γ_M) and highly reflective (Γ_R) power detectors, compared against the measurement done using a commercial VNA: (a) 1-dB attenuator, (b) 2-dB attenuator, (c) 3-dB attenuator, (d) 6-dB attenuator, and (e) 10-dB attenuator.**

comparable to the one obtained for PSP. However, in conjunction with highly reflective power detectors RSP, the measurement error increases significantly, which fully corresponds

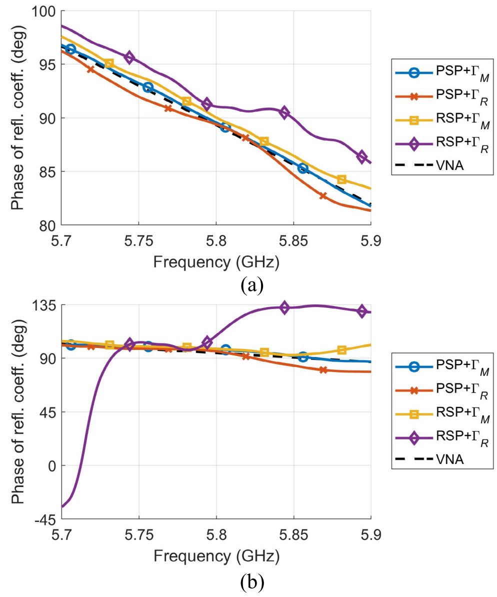


FIGURE 14. **Phase of reflection coefficients of (a) 1-dB and (b) 10-dB attenuator terminated with a short-circuit measured using reflectometer with the proposed (PSP) and the reference (RSP) six-port network, with well-matched (Γ_M) and highly reflective (Γ_R) power detectors, compared against the measurement done using a commercial VNA.**

to the predictions made on the basis of the circle centers' distribution of RSP presented in Fig. 12(b) in the previous section.

Having the experimental verification completed, it is seen that the proposed six-port reflectometer is insensitive to power detectors' reflection coefficients. As presented in Section IV, a very good performance can also be achieved even with a distinct discrepancy of these reflection coefficients. This feature makes the presented six-port unique, as no other reported solution is capable of correct measurements if power detectors are not matched. Simultaneously, the circuit complexity is the same as in case of other reflectometers. Comparing the topologies shown in Fig. 1 and Fig. 2 it can be observed, that the proposed six-port as well as other solutions are composed of five couplers/dividers. Thus, the occupied area is also comparable. Finally, the proposed six-port reflectometer exhibits the optimum circle centers distribution, which minimizes the measurement uncertainty for all measured reflection coefficients, for which $|\Gamma| < 1$. All the advantages given above make it a perfect candidate for application in six-port measurements.

IX. CONCLUSION

In this paper, a new topology of six-port reflectometer was presented. In contrast to all previously reported solutions, it exhibits a high immunity to power detectors' impedance mismatch, and simultaneously it provides optimum measurement conditions leading to low measurement error. A comprehensive theoretical analysis allowed for formulating relation between the measured reflection coefficient and power readings. It also showed that the signals reflected from non-matched power detectors do not affect the desired signal propagation in the six-port network, hence no impairment of the measurement performance is expected. This was experimentally confirmed and compared against reflectometer incorporating the reference six-port network. Both reflectometers were designed and fabricated, calibrated and then used to measure complex reflection coefficients. Calibration and measurements were performed for both reflectometers with well-matched power detectors, as well as with highly reflective ones. It was demonstrated that by application of the proposed six-port the reflection coefficient measurement can be equally successfully performed with both types of power detectors, whereas the reference reflectometer cannot operate properly with non-matched power detectors. It is therefore proven that a development of six-port reflectometers can be greatly simplified, as impedance matching networks for power detectors may be neglected. This advantage of the proposed six-port reflectometer becomes even more significant in wideband measurement systems utilizing diode power detectors, for which dedicated matching network would be difficult to realize and would occupy a significant area. Hence, further research will be focused on extending the frequency bandwidth leading to development of a compact and low-cost measurement solutions.

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