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Microwave Eight-Port Reflectometer for Air Pollution Sensor

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***Abstract*—In this paper, a microwave reflectometer incorporating eight-port network is presented. It is designated to measure reflection coefficient of an air pollution sensor. The reflectometer operates at the frequency of 5.8 GHz and exhibits simplified circuitry with respect to previously reported solutions. Simultaneously, it provides tunable power distribution scheme, which serves for optimizing the measurement uncertainty for a chosen sensor. As a consequence, the uncertainty can be greatly minimized comparing to other reflectometers with fixed power distribution scheme. The developed eight-port has been fabricated and used to developed measurement setup. Finally, the reflectometer has been calibrated for two exemplary settings proving experimentally its tuning capability.**

Keywords*—microwave reflectometer, reflection coefficient, power distribution network, power detectors, calibration.

I. Introduction

Clean air is vital for people's health and the environment. Nowadays, air pollution has reached an alarming level, therefore it is crucial to monitor particulate matters (PM2.5, PM10) and NO_2 to efficiently control the emissions. In literature a rapid development of gas sensors can be observed [1, 2]. Currently, microwave-based sensors are becoming more and more attractive, due to their capability of room temperature operation [3, 4], which significantly enhances energy efficiency needed in mobile applications. To address required high sensitivity of a gas sensor, its response under gas exposure must be precisely measured. At microwave frequencies the mentioned response is usually defined as the sensor's reflection coefficient. Such value can be measured with a vector network analyzer, which is a bulky, highly complex and expensive equipment. To suppress the measurement circuitry and simultaneously sustain high measurement accuracy a multiport reflectometer can be used [5, 6]. It is a passive power distribution network with signal source and RF power detectors connected. Thanks to a suitable power distribution, the power readings can easily be transformed into a vector value of the reflection coefficient.

Multiport reflectometers in general are designed to optimize measurement conditions for all reflection coefficients of passive devices, meaning that measured reflection coefficient Γ can have arbitrary phase and magnitude not exceeding unity [7, 8]. Such an approach makes the reflectometer a useful and universal measurement apparatus. However, as it has recently been shown in [9, 10], a multiport reflectometer can be optimized for much narrower range of the measured reflection coefficient e.g., for a small area close to an optimal reflection coefficient Γ_{ref}. As a consequence, the measurement accuracy for this range can be significantly enhanced, which is especially important in sensor application, where the measured reflection coefficient's dynamics is expected to be relatively low. Therefore, the measurement uncertainty for remaining reflection coefficient values is increased, however, they are never measured by the reflectometer. As a consequence, the measurement uncertainty in the range of interest can be even better than the measurement uncertainty of commercially available vector network analyzers [10]. It is noteworthy that such an enhancement is only achieved by an appropriate design of the reflectometer.

In this paper we present a microwave multiport reflectometer intended for air pollution sensing. It is a version of the reflectometer reported in [10] simplified to meet requirements for mobile application. The presented reflectometer operates at a single frequency of 5.8 GHz, thus wideband components, such as multisection coupled-line directional couplers are no longer needed. Instead, simple branch-line couplers are applied, which are feasible with the use of single metallization layer. Simultaneously, due to single-frequency operation, the signal source can be significantly simplified in target application with respect to the swept-frequency source used in [10]. As a result, a significant size reduction is achieved. The designed reflectometer has been manufactured and characterized by measuring its scattering parameters, which show good performance. Finally, the manufactured reflectometer has been calibrated to show its advantageous properties in the target application.

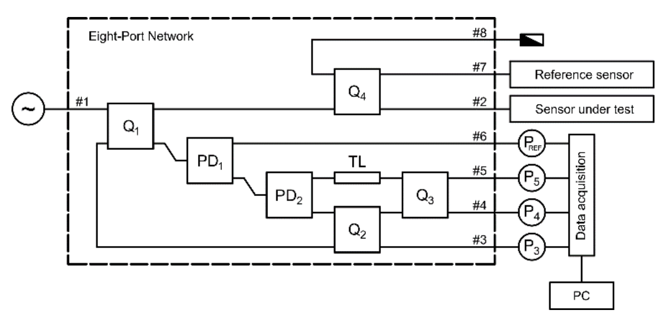

Fig. 1. A diagram of the developed eight-port reflectometer.

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II. PRINCIPLE OF OPERATION

Fig. 1 presents a schematic diagram of the proposed multiport reflectometer. Its key element is the eight-port network having the topology presented in [10], to which other components are connected. It is composed of four quadrature couplers $Q_1 – Q_4$, two in-phase power dividers PD_1 and PD_2, and a transmission line TL to equalize the electrical length of appropriate signal paths. The reflectometer is fed at port #1 by a continuous-wave signal which is distributed to all remaining ports of the eight-port network. The wave delivered to port #2 with the sensor, the reflection coefficient Γ of which is the subject to measure, is reflected and distributed again through the eight-port network to ports #3 – #5 with power detectors $P_3 – P_5$ connected. Hence, these three power detectors measure the power of two interfering signals: the one delivered directly from signal source, and the second one reflected from the sensor. This interference constitutes the general principle of operation of multiport reflectometers [5-8]. Moreover, the reference sensor connected to port #7 allows for adjusting the power distribution scheme in order to optimize the measurement uncertainty for the measured sensor's reflection coefficient [10], as will be described further in this section. Finally, port #6, being isolated from ports #2 and #7 with the sensors, serves for a reference power measurement i.e., for measurement of power transmitted directly from the feeding port #1. The remaining port #8 is unused, and should be terminated with a matched load. The normalized power p_i measured by the i-th power detector (i = 3, 4, 5) is equal to:

$$p_i = \frac{P_i}{P_{REF}} = q_i \left| \frac{1 + A_i \Gamma}{1 + A_0 \Gamma} \right|^2 \qquad (1)$$

where q_i, A_i, and A_0 are calibration parameters, which result from the reflectometer's topology and need to be found using a calibration procedure.

The calibration constants in (1) have a crucial impact on the measurement uncertainty. Using the well-known geometrical interpretation of (1) the measured reflection coefficient Γ can be illustrated as a point where three circles intersect on a complex plane [8-10]. Centers of these circles c_i can be derived as:

$$c_i = -\frac{1}{A_i} \qquad (2)$$

whereas their radii depend on the measured power p_i:

$$r_i = \sqrt{\frac{P_i}{q_i |A_i|^2}} \qquad (3)$$

It should be underlined that (2) and (3) hold if the coefficient A_0 in (1) is close to zero, which is usually fulfilled in practical realizations. Usually, multiport reflectometers are optimized to measure all reflection coefficients of passive devices. For this scenario the optimum arrangement of circle centers is composed of three points arranged uniformly on the unitary circle [7], as it is illustrated in Fig. 2. In such a case all reflection coefficients having the magnitude not exceeding unity are considered. However, as it is described in [9] and [10], in sensor applications such full range of the reflection coefficient Γ is not useful, as the tested sensor's reflection varies only insignificantly. Thus, the measurement range can be scaled down to a smaller fraction of the unitary circle, as indicated in Fig. 3. As can be observed all three points c_i are located relatively close to each other, which optimizes the measurement uncertainty for the area with the optimum point Γ_{ref}. As a consequence, a small change of reflection coefficient (caused by sensor's exposure to gas) is reflected in higher relative change of the circles' radii r_i given by (3) and presented in Fig. 4, in comparison to the conventional circle centers' distribution illustrated in Fig. 2. Subsequently, the increased dynamics of measured power suppresses the power measurement uncertainty, which finally results in a lower reflection coefficient's measurement uncertainty [9, 10]. The point of the optimum measurement uncertainty Γ_{ref} is equal to the reflection coefficient seen at port #7 of the eight-port network. Hence, to optimize the measurement uncertainty for the tested sensor, an identical (or similar) sensor should be connected to port #7 as a reference reflection coefficient. Such an approach additionally allows for compensation of the sensor's reflection coefficient change over frequency and temperature. Alternatively, arbitrary impedance can be connected to optimize measurement uncertainty for the needed range.

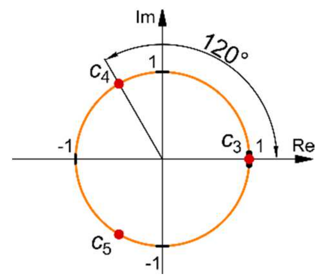


Fig. 2. Optimum arrangement of circle centers for measurement of all reflection coefficients of passive devices, for which $|\Gamma| \leq 1$.

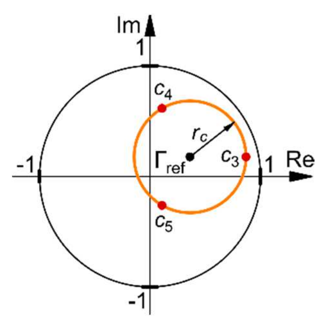


Fig. 3. Arrangement of circle centers' optimized for a narrow proximity of the selected point Γ_{ref}.

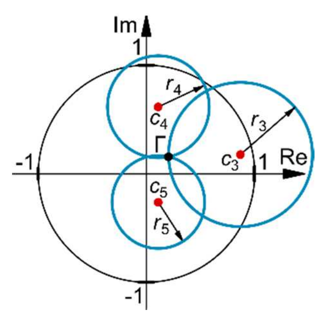


Fig. 4. Intersection of three circles indicating the measured reflection coefficient Γ for the arrangement of circle centers optimized for a narrow proximity of the selected point Γ_{ref}.

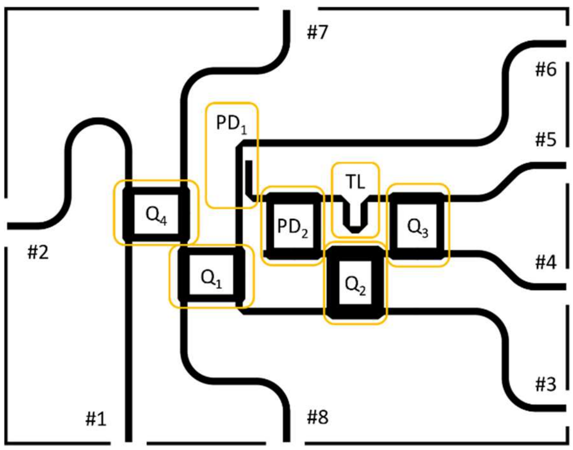


Fig. 5. Layout of the designed eight-port reflectometer.

III. Design of the Eigth-Port Reflectometer

The eight-port reflectometer has been designed for the center frequency of 5.8 GHz. It is a compromise between circuitry miniaturization, sensitivity, and cost of active components. It is known that the sensors operating at higher frequencies exhibit higher reflection coefficient's phase change to a gas exposure [10]. Moreover, the higher frequency is, the smaller the circuit becomes. However, such a miniaturization makes the fabricated elements more prone to manufacturing intolerances. Furthermore, the developed reflectometer is designated for a high-volume production, hence low-cost active elements, such as signal source and power detectors have to be used, and their price increases significantly with frequency.

To address the cost-related requirements the eight-port network has been designed using single metallization layer, using microstrip technique and RO4003 laminate by *Rogers*. The substrate height equals 0.508 mm and its permittivity is equal to 3.55. The couplers Q_1 – Q_4 have been realized as branch-line couplers; couplers Q_1, Q_3, and Q_4 feature equal-power split, whereas, coupler Q_2 provides power split ratio 2:1 [10]. The power divider PD_1 has been realized as a single-section of edge-coupled lines with the coupling factor $k = 0.1$ ($C = 20$ dB). Such a value provides the radii of the circle along which circle centers c_i are arranged equal to $r_c = 2k\sqrt{2} \approx 0.28$ [10]. To realize the remaining power divider PD_2 the same branch-line direction coupler as Q_1, Q_3, and Q_4 has been utilized, however the unused port is left open. The designed eight-port network's layout is illustrated in Fig. 5, whereas the measured *S*-parameters of the manufactured network are depicted in Fig. 6. As seen the fabricated eight-port network exhibits a very good impedance match at the input port #1, the measurement port #2 and the port #7 for the reference sensor. Impedance matching of other ports does not affect the measurements. The transmission coefficients seen in Fig. 6(b) also meet the theoretical expectations. In particular, transmission coefficients from input port to ports with sensors (S_{21} and S_{71}) are very close to each other, transmission coefficients from measurement port to power detectors (S_{32}, S_{42}, and S_{52}) are also close to each other. A distinctly higher discrepancy occurs for transmission coefficients from input port to ports with power detectors (S_{31}, S_{41}, and S_{51}), which is most probably due to their low level being comparable with isolations

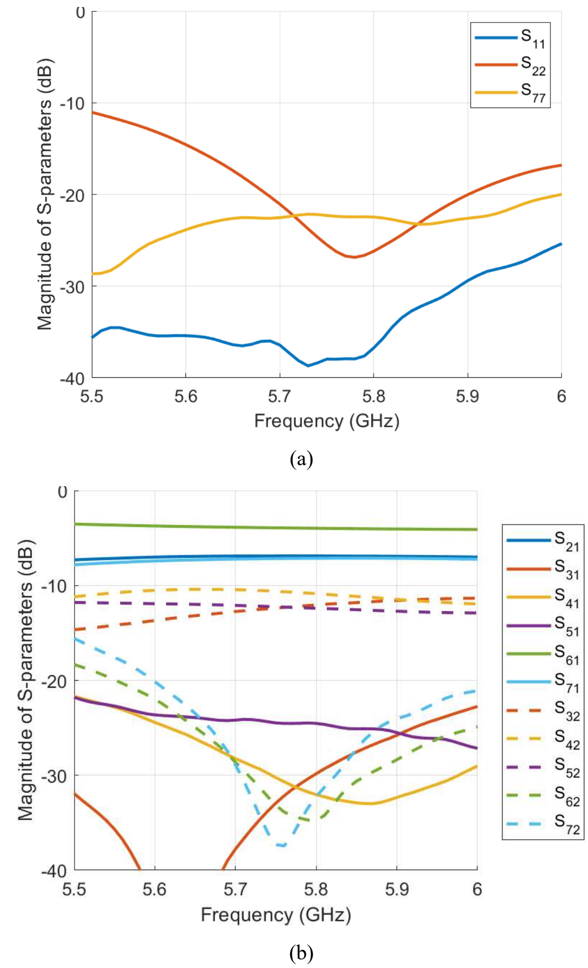


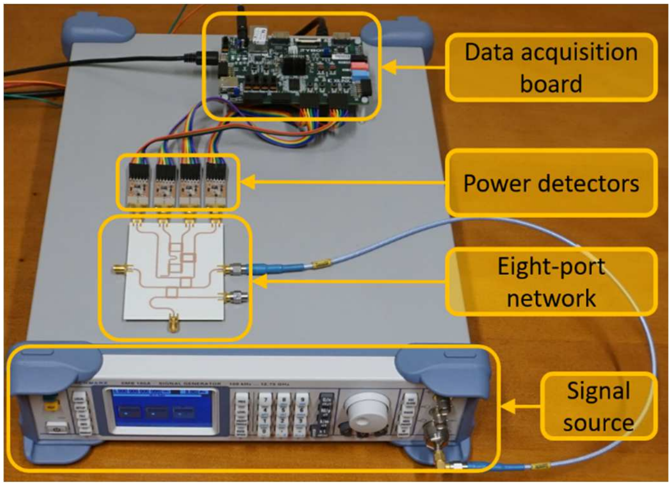
Fig. 6. Measured *S*-parameters of the fabricated eight-port reflectometer: (a) impedance match and (b) transmission coefficients.

of the branch-line couplers. Additionally, a good isolation has been achieved between the port for reference power measurement and ports with sensors connected (S_{62}, and S_{72}).

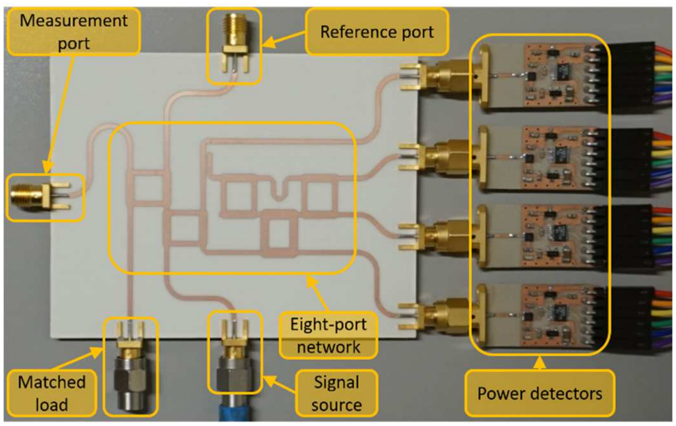
IV. Measurement Setup and Calibration

The fabricated eight-port network has been incorporated to develop the reflectometer's setup. As the signal source connected to port #1 laboratory signal source *Rohde&Schwarz* SMB 100A has been used. It provides 0 dBm of continuous wave signal at 5.8 GHz. For the power measurement four integrated power detectors LTC5597 by *Analog Devices* have been applied. At the frequency of interest, they exhibit a linearity error not worse than ±0.3 dB within the measured power range from -35 dBm to 0 dBm, which is more than sufficient for the application. To improve the linearity, the power detectors have been previously calibrated by forming Loo-Up Tables (separate for each detector), which efficiently suppress the non-linearity. The developed measurement setup is illustrated in Fig. 7.

To verify the measurement performance of the developed reflectometer its circle centers' distribution has been derived following the calibration method described in [11]. It utilizes measurements of several known terminators with known reflection coefficients. In particular they are, 50Ω load, open-



(a)



(b)

Fig. 7. Photograph of the developed eigth-port reflectometer: (a) general view and (b) closer view on the eight-port network with power detectors.

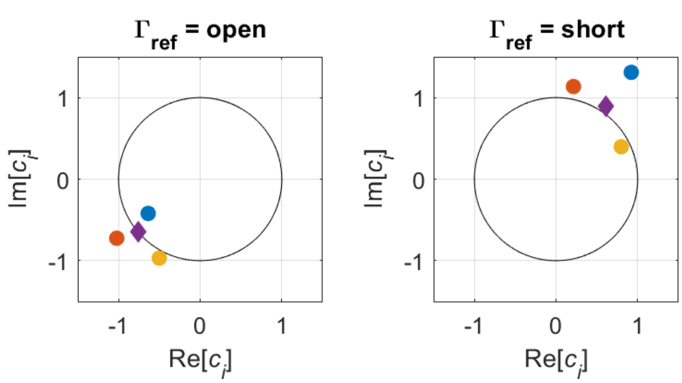


Fig. 8. Circle centers' distributions obtained for the developed eight-port reflectometer during calibration done for open- and short-circuit connected to port #7. ● – circle centers c_i, ♦ - Γ_{ref}.

circuit, short-circuit, and open- and short-circuit with a short section of transmission line to ensure required phase offset. The calibration has been performed twice: for open-circuit and for short-circuit connected to port #7. Following theoretical assumptions, their reflection coefficients should constitute the center of optimum area on the complex plane, for which the measurement uncertainty will be the lowest. The obtained circle centers' distributions are depicted in Fig. 8. As can be observed both distributions exhibit uniform arrangement of circle centers c_i around Γ_{ref}. The distributions are shifted by 180° with respect to each other, which results from the 180° of phase difference between open- and short-circuit's reflection coefficient used as Γ_{ref}. As seen the mutual arrangement of circle centers can be efficiently adjusted by connecting an element exhibiting desired reflection coefficient to port #7 of the eight-port network.

V. Conclusions

In this paper the eight-port reflectometer intended for mobile application in air pollution measurement has been presented. It has been realized as a simplified modification of the work reported in [10]. By utilizing a single metallization layer and single frequency operation the circuitry's complexity has been significantly reduced. The designed eight-port network has been fabricated and characterized by its *S*-parameters measurement. They prove its usefulness in reflection coefficient measurements. Finally, the entire reflectometer incorporating the eight-port network has been developed. The calibration done for two different one-ports serving as the reference reflection coefficient Γ_{ref} shows that the circle centers' distribution can easily be adjusted to optimize it for the reflection coefficient of an air pollution sensor' reflection coefficient, which will be the sensing element of the entire system.

References

[1] I. Christakis, G. Hloupis, I. Stavrakas and O. Tsakiridis, "Low cost sensor implementation and evaluation for measuring NO_2 and O_3 pollutants," 2020 9th International Conference on Modern Circuits and Systems Technologies (MOCAST), Bremen, Germany 202, pp. 1-4.

[2] R. Ghosh, J. W. Gardner, and P.K. Guha, "Air pollution monitoring using near room temperature resistive gas sensors: A review", IEEE Trans. Elec. Dev., vol. 66, no. 8, pp. 3254-3264, August 2019.

[3] G. Bailly, A. Harrabi, J. Rossignol, M. Michel, D. Stuerga, and P. Pribetich, "Microstrip spiral resonator for microwave-based gas sensing," IEEE Sens. Lett. vol. 1, no. 4, pp.4500404, August 2017.

[4] M.H. Zarifi, A. Sohrabi, P.M. Shaibani, M. Daneshmand, and T. Thundat, "Detection of volatile organic compounds using microwave sensors," IEEE Sens J., vol. 15, no. 1, pp. 248-254, January 2015.

[5] S. O. Tatu, A. Serban, M. Helaoui, and A. Koelpin, "Multiport technology: The new rise of an old concept," IEEE Microw. Mag., vol. 15, no. 7, pp. 34-44, November 2014.

[6] A. Koelpin, G. Vinci, B. Laemmle, D. Kissinger, and R. Weigel, "The six-port in modern society," IEEE Microw. Mag., vol. 11, no. 7, pp. 35-43, November 2010.

[7] K. Staszek, S. Gruszczynski, and K. Wincza, "Six-port reflectometer providing enhanced power distribution," IEEE Trans. Microw. Theory Techn., vol. 64, no. 3, pp. 939-951, March 2016.

[8] G. F. Engen, "A (historical) review of the six-port measurement technique," IEEE Trans. Microw. Theory Techn., vol. 45, no. 12, pp. 2414-2417, December 1997.

[9] K. Staszek, A. Szkudlarek, M. Kawa, and A. Rydosz, "Microwave system with sensor utilizing GO-based gas-sensitive layer and its application to acetone detection," Sens. Actuators B, vol. 297, pp. 1-10, October 2019.

[10] J. Sorocki, A. Rydosz, and K. Staszek, "Wideband microwave multiport-based system for low gas concentration sensing and its application for acetone detection," Sens. Actuators B, vol. 323, pp. 1-12, November 2020.

[11] K. Staszek, P. Kaminski, A. Rydosz, S. Gruszczynski, and K. Wincza, "A least-squares approach to the calibration of multiport reflectometers", in Proc of. Int. Microw. & RF Conf., Delhi, India 2013, pp. 1-4.