VĚDECKÉ SPISY VYSOKÉHO UČENÍ TECHNICKÉHO V BRNĚ

Edice PhD Thesis, sv. 527

ISSN 1213-4198

Ing. Tomáš Urbanec

Special Methods for Microwave Vector Measurements

BRNO UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING
AND COMMUNICATION

DEPARTMENT OF RADIO ELECTRONICS

Ing. TOMÁŠ URBANEC

SPECIAL METHODS FOR MICROWAVE VECTOR MEASUREMENTS

SPECIÁLNÍ METODY MIKROVLNNÝCH VEKTOROVÝCH MĚŘENÍ

DISSERTATION THESIS SHORT VERSION

Obor:	Elektronika a sdělovací technika
Školitel	Prof. Ing. JIŘÍ SVAČINA CSc.
Oponenti:	Prof. Ing. KAREL HOFFMANN CSc.
	Prof. Ing. IVAN KNEPPO DrSc.
Datum obhajoby:	28. 3. 2008

KLÍČOVÁ SLOVA
Vektorová měření, měřící metoda šestibranu, vektorový obvodový analyzátor, činitel odrazu, širokopásmová měření, kalibrace.

KEYWORDS
Vector measurements, sixport measurement method, vector network analyzer, reflection coefficient, wideband measurements, calibration.

MÍSTO ULOŽENÍ PRÁCE / STORAGE PLACE OF WORK
Vědecké oddělení FEKT VUT v Brně, Údolní 53, 602 00 Brno

ISBN 978-80-214-3898-9

ISSN 1213-4198

TABLE OF CONTENTS

1 INTRODUCTION

With the growth of the microwave technology use there is the everlasting demand for measurement. Measurements consists of scalar and vector measurements, former allow for measurement of amplitudes whereas latter allow for measurement of both amplitudes and phases of signals. Scalar measurements are sufficient in the case of power measurement, signal loss or standing wave ratio but for measurement of impedances, antenna phasing, complete circuit description and other, the vector measurements are necessary.

Vector measurements have an important role not only in microwave technology, but also in medicine, diagnostics and industry applications and in many more places.

Standard way for vector measurements is the use of vector network analyzer, which allows the measurement in the very wide frequency band with high precision of both amplitude and phase of signals. For the precise results we pay by the very complicated design of vector network analyzer and therefore such a piece of equipment is rather expensive.

For the above mentioned reasons there is always a need for alternative approaches, how to do the vector measurements. The one from the used approaches is method of sixport, which by the use of four power measurements is able to determine the complex reflection coefficient.

Other known methods are slotted line reflectometer, which is the oldest method known, method of fiveport, method of perturbated twoport and many more.

2 STATE OF THE ART

2.1 SLOTTED LINE METHOD

This is the oldest method used and for realization it is necessary to have appropriate slotted line for the frequency of measurement. At the lower frequencies, the coaxial line is used, in the microwave region the slotted waveguide must be used.

The method works with measurement of standing waves, by measurement of minimum and maximum voltage it is possible to obtain standing waves ratio and then absolute value of reflection coefficient. By measurement of distance between minimum and minimum when short was connected, it is possible to calculate argument of reflection coefficient.

2.2 METHOD OF PERTURBATED TWOPORT

In the year 1998 it was published by Hoffmann and Škvor in [1], as possible addition for scalar network analyzer. It is done by four measurements of reflected power. First measurement is done with device under test connected right to scalar network analyzer, for other three measurements there are inserted between them various twoports so called perturbation twoports.

Their purpose is to transform the reflection coefficient of device under test and its amplitude is measured by scalar network analyzer. In such a way we obtain set of four values which are influenced by inserted twoports. From those values it is possible to calculate the complex reflection coefficient. For the calibration purposes it is necessary to know all of the scattering coefficients of perturbation twoports.

2.3 VECTOR NETWORK ANALYZER

The vector network analyzer is the most used system for the measurement of complex reflection or transmission coefficient. It is possible to measure with it in the very wide frequency region with small error. With the ability of connection with the computer technique, it is possible to do further corrections of measured characteristics and to suppress possible errors of analyzer, then the precision of hundredth of dB and tenths of degrees is possible.

The basic principle follows. Signal from generator is splitted into two parts, one goes to analyzer as a reference signal, second part goes to device under test and measured signal is obtained with directional coupler as signal reflected from device under test, or transmitted through the device under test. With the use of multiple frequency conversions signals at intermediate frequency are obtained and here is produced the amplitude ratio and phase difference between the reference and measured signal. The most complex part of the system is the frequency conversion, because it must work in the whole frequency band of vector network analyzer [2].

2.4 MICROWAVE SIXPORT METHOD

2.4.1 Principle of Method

With the growing need of vector measurements at microwave frequencies question arises, whether such a method exists, which can substitute the classical vector network analyzer and avoid its complex circuit construction. In the 1970th G. F. Engen published in [3] proposal of the method which is able to measure both amplitude and phase of microwave signal with the aid of four detectors, which measure powers of microwave signals. The method allows moving the complexity of vector network analyzer towards the software in the post processing of measurement. With the computing power growing such a method tends to be preferable as time and cost effective.

Basic arrangement of the method can be seen in the Fig.1a). Generator is connected to port 1, device under test is connected to port 2 and power is measured at ports 3 to 6. There can be written $\rho = a_2 / b_2$, where ρ is the unknown reflection coefficient at port 2 and a_2 a b_2 are reflected and incident wave respectively at this port. By assuming the sixport is linear circuit it is possible to write

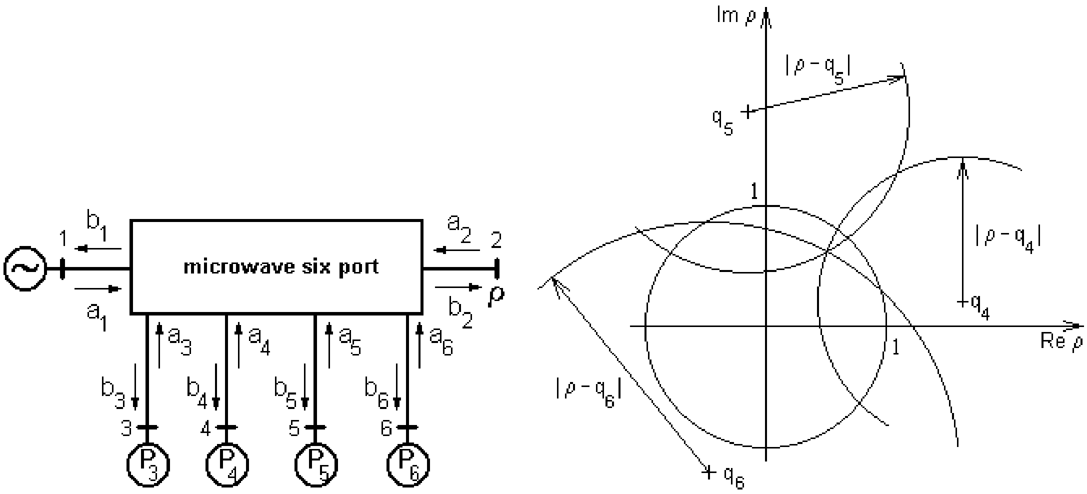


Fig.1a) Basic arrangement of microwave sixport method, 1b) Principle of measurement

$$P_3 = \left|\mathrm{A} \cdot a_2 + \mathrm{B} \cdot b_2\right|^2 \quad , \tag{1}$$

where measured power at port 3 is P_3 and A, B are complex constants describing sixport. Accordingly it is possible to describe ports 4 to 6 with respective powers P_4, P_5 and P_6. From the practical point of view it is suitable to opt for A=0. In this way power at port 3 is proportional to generator power only and is independent of reflection coefficient value at port 2. Such a decision is concretizing the common sixport slightly but it is possible to take it as simplification only and for obtaining of precise results it is better to use the formula (1). For obtaining the reflection coefficient ρ in the formula, we can modify it

$$P_4 = \left|\mathrm{C}\right|^2 \cdot \left|b_2\right|^2 \cdot \left|\rho - q_4\right|^2 \quad , \tag{2}$$

where q_4=-D/C and accordingly it is possible to get formulas for powers P_5 and P_6. It is possible then to find a solution for ρ, but for general idea about the method it is possible to use in formulas (2) b_2 expressed from (1) and obtain

$$\left|\rho - q_4\right|^2 = \frac{P_4}{P_3} \cdot \left|\frac{\mathrm{B}}{\mathrm{C}}\right|^2 \quad , \tag{3}$$

The geometrical implementation of formula (3) can be seen in the Fig. 1b). The results of the formula create the circle in the impedance plane with the center in point q_4 and radius of $|\rho - q_4|$. Next formula creates second circle, which intersect the first in two points. If we assume measurement of passive circuits with $|\rho| \leq 1$, then the unknown result lies inside of the unity circle, in the intersection. If the connection of q_4 a q_5 lies out of unity circle, then one of intersections will lie outside too. It can be seen, that unique result exists even without the use of third formula. In that case it would be method of fiveport. The main disadvantage of such method is bigger error in result estimation, because in the case of intersection of circles with small angle between them, the method is very sensitive to accuracy of measurement and noise present.

With the use of third equation similar to (3), the last circle is created. In the ideal situation the intersection of all circles is situated in one point.

In the above description we were assuming the validity of equation A=0, but in reality it is approximation only. Generally we obtain circle too, but with center lying on line between points q_4 and q_5. There the position of center is not a constant and it depends on actual ratio of P_4, P_5.

2.4.2 Practical Circuits for Microwave Sixport

From the above mentioned some requirements for circuit arise, which must be fulfilled for the proper functionality of the method:

- Power at one port should be dependent on generator signal only for the simplest solution of the equations (A=0).
- Distance of center q points from the origin should be approximately 1.5 [3].
- The center q points should be evenly distributed around unity circle ideally by 120° for the explicitness of solution and noise robustness.

The typical representatives of microwave sixports can be seen in Fig.2. The classical schematics of the sixport known from the first proposal of technique in [3] can be seen in Fig.2a). The main purpose was measurement at high microwave frequencies and the appropriate realization was therefore by waveguide technology. Circuit consists of quadrature and 180° hybrids and 6 dB directional coupler. Due to the waveguide technology, the maximum frequency range was 1 : 2. Precision positioning of q points was essential, because results were obtained by sums and subtractions of detected powers only and calibration of measurement was done at single frequency. With the development of computer technology, the applications of it for the calibration and automation of measurement were developed. It was then possible to use the sixports with simpler design, or to make measurements in the wider frequency range.

Next generation sixport can be seen in Fig.2b) where very simple circuit [4] is used consisting of three coupled microstrip lines. Z_s is the wideband short. Such a circuit is not keeping the precise q points distribution and their position is frequency dependent. With the use of wideband calibration it is not a problem any more. Obtainable frequency range is up to 1 : 10.

This design shows definite movement from precise and therefore costly designs to simple ones. The nonideal parameters can be suppressed by calibration with the use of computer post processing. Similar design is also the directional coupler with the symmetrical lossless fiveport. Such concept [5] is very simple also and it is relatively wideband too.

Third generation type of sixport [6] can be seen in Fig.2c), the main parameter is extreme wideband behavior up to three decades. It was realized for the frequency band between 2 and 2000 MHz. Lumped elements L, C present phase shift for low frequencies, where lengths of lines have no influence. Lines work on higher frequencies where L and C represent high resp. low impedance. It is necessary to suppress all resonances and therefore rapid phase changes. That is done by the use of separation resistors, which work as impedance matching. The price for such matching is high transmission loss approx. 20 dB.

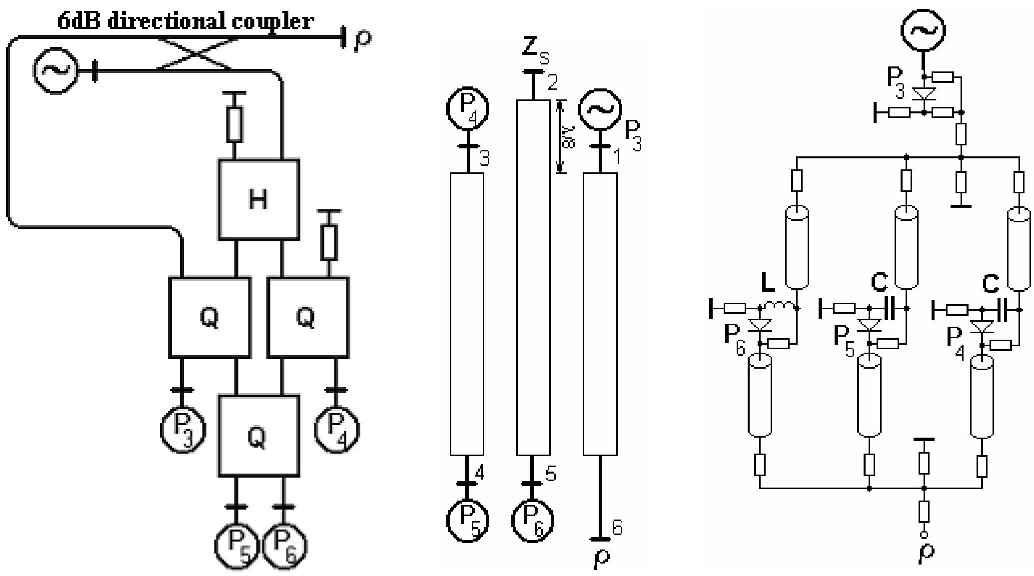


Fig.2 a) Classical sixport design, b) Sixport from three coupled microstrip lines, c) Wideband sixport as combination of lumped and distributed circuits

2.4.3 Calibration Method

Better description for the measurement and calibration purposes than according to (3) exists. From [7] it can be written

$$\rho = r + \mathrm{j}x = \frac{\sum_{i=1}^{4} (\mathrm{F_i} + \mathrm{jG_i}) \cdot P_i}{\sum_{i=1}^{4} \mathrm{H_i} \cdot P_i} \quad , \tag{4}$$

where ρ is the unknown reflection coefficient and F_i, G_i a H_i are real constants describing the sixport and P_i are the measured powers. The equation can be normalized for example to H_4 constant and for solution of equation it is necessary to know eleven constants of sixport. Those can be found with the suitable calibration process according to (4) using set of known impedances, connected in sequence to measurement port. The equation (4) can be rewritten to two separate equations for real and imaginary parts

$$\sum_{i=1}^{4} \mathrm{F_i} \cdot P_i - r \cdot \sum_{i=1}^{3} \mathrm{H_i} \cdot P_i = r \cdot P_4 \ , \ \sum_{i=1}^{4} \mathrm{G_i} \cdot P_i - x \cdot \sum_{i=1}^{3} \mathrm{H_i} \cdot P_i = x \cdot P_4 \ . \qquad (5), (6)$$

Those equations are suitable for measurement calibration. With the use of seven different known impedances it is possible to do whole calibration. Due to the measurement errors or noise it is not working properly always. It is possible then to use other methods described in [8].

2.5 INFLUENCE OF THE DISTANCE BETWEEN Q POINTS AND CENTER OF UNIT CIRCLE

As it was mentioned previously in the chapters 2.4.1 and 2.4.2, it is necessary to select distance of q points from the center of impedance circle for the correct operation of sixport. The distance is determined by transmission losses between the detectors and measurement port.

If the losses will be negligible, the q points will lay on unity circle. With the growing losses the q points will move away from the unity circle. We can assume that $U_0 = q$, $U_{\min} = q - 1$ and $U_{\max} = q + 1$, where q is the distance from the impedance circle center. $U_{\max}$ and $U_{\min}$ are maximum and minimum values of voltage respectively in the case of measurement impedance $|\rho| = 1$, the L is inserted loss between detectors and measurement port. Then it is possible to describe the dependence between q and L by the following equation and express the necessary measurement dynamic range

$$D = 20 \cdot \log\left(\frac{U_{\max}}{U_{\min}}\right) = 20 \cdot \log\left(\frac{q+1}{q-1}\right) = 20 \cdot \log\left(\frac{10^{\frac{2L}{20}} + 1}{10^{\frac{2L}{20}} - 1}\right). \tag{7}$$

When we use for the measurement the diode detectors in the quadratic detection area, the output voltage will be proportional to input power of detectors. It is necessary to convert the voltages of detectors for the further use in PC with the use of A/D converter. We will assume n bit converter with the 2^n levels. It is possible then to find the boundary values of measurement

$$P_{\max} = 2^n - 1,\ P_0 = \frac{2^n - 1}{\left(1 + 10^{\frac{-2L}{20}}\right)^2},\ P_{\min} = \frac{\left(2^n - 1\right) \cdot \left(1 - 10^{\frac{-2L}{20}}\right)^2}{\left(1 + 10^{\frac{-2L}{20}}\right)^2} \qquad (8), (9), (10)$$

It can be seen, that with the L growing, the use of converter lowers and by the losses of approx. 7 dB, the measurement uses just one half of the converter range. We can write equation for measured power of actual scattering coefficient S_{11} in dB as

$$P_m = \frac{\left(2^n - 1\right) \cdot \left(1 \pm 10^{\frac{-2L}{20}} \cdot 10^{\frac{S_{11}}{20}}\right)^2}{\left(1 + 10^{\frac{-2L}{20}}\right)^2}, \tag{11}$$

where the sign ± depends on S_{11} phase, whether there is summation of voltages, or its difference. We can derive the equation (11) with respect to S_{11} and reorganize; then we get the resolution of measurement in dB per converter level

$$f_{\text{resm}} = \frac{1}{P_{\text{m}}'} = \pm\frac{1}{\left(2^{\text{n}}-1\right)}\frac{10}{\ln(10)}\frac{\left(1+10^{\frac{-2L}{20}}\right)^2}{\left(1\pm10^{\frac{S_{11}-2L}{20}}\right)\cdot10^{\frac{S_{11}-2L}{20}}}. \tag{12}$$

The results of f_{resm} in dependence on measured S_{11} and L can be seen on Fig.3. There are two attributes of characteristics. The first feature can be seen as intersection between curves and the x axis, which means that with L growing the dynamic range lowers but not with the same speed. The second feature is the more important, where nearby y axis, around $S_{11}\approx0$ dB the sensitivity of measurement greatly deteriorate with small values of L. That means the necessity of measurement of small amounts of power with high dynamic range requirement. There can be seen two curves for each value of L in the Fig.3 describing both results of equation (12). Here can be seen the optimum value of L for sixport design in the range between 1.6 dB and 3 dB. With bit width n change it is possible to move in dynamic range for the same resolution.

For the available value of S_{11} with the assumption of linear parts of curves in Fig. 3 we can write

$$S_{11} = -6.02\cdot\text{n} - 20\cdot\log\left(f_{\text{resm}}\right) + 0.0829\cdot L^2 + 0.164\cdot L + 24.6, \tag{13}$$

which holds for precision better than circa ±0.5 dB for results S_{11}<-15 dB.

In the previous part the impacts of q points position on measurement were described. The simplest setting can be done by resistive attenuator, which is wideband solution. In the real design, losses in the materials are present and mainly on higher bounds of frequency range must be taken into account.

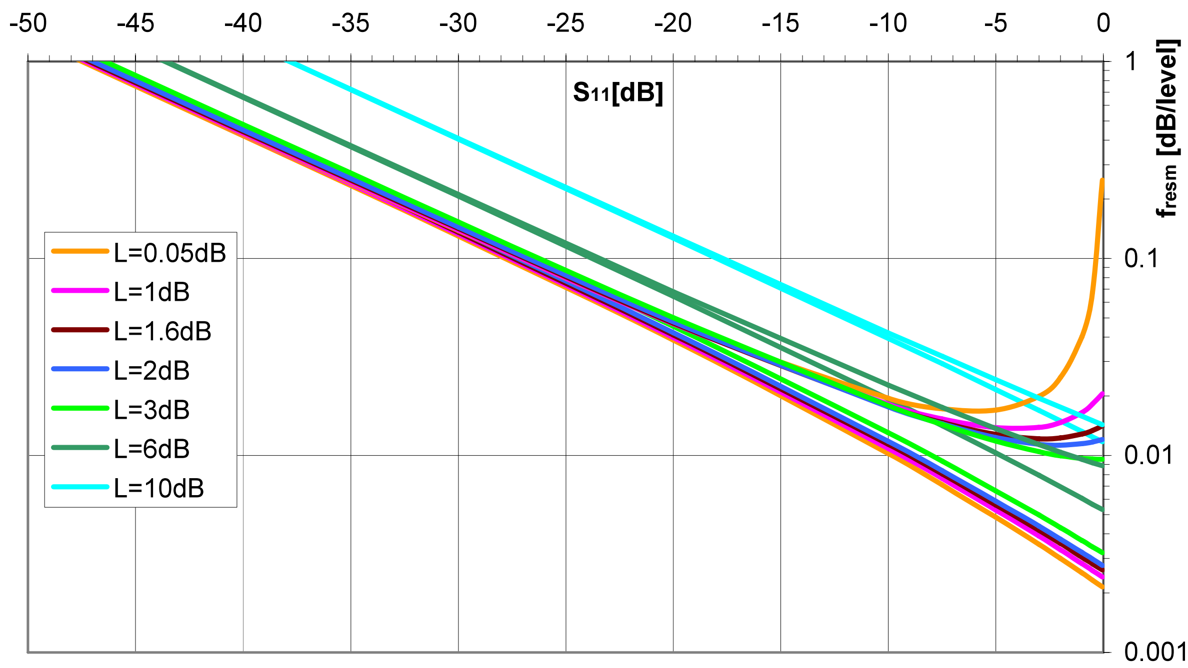


Fig.3 The influence of inserted loss L on measurement resolution in case of 12 bit A/D converter.

2.6 POSITION OF Q POINTS AROUND UNIT CIRCLE

The q points must be properly distributed around unity circle to have the sixport working properly. That can be done by insertion of suitable twoports between each pair of detectors or the detectors can be situated on ports of more complicated circuit. Typical solutions were described previously on Fig.2. Every solution brings other advantages, but main purpose is to obtain the maximum bandwidth. The aim of solutions is to hold the angles α_1, α_2 a α_3 in suitable range. From previous work [9] can be seen, that angles should be greater than 15°, to have majority of calibration methods working. Optimum value of angles is 120°, but that can be fulfilled on single frequency only.

The simplest schematics of the sixport just transposed to technology suitable for PCB originating in [10] can be seen in Fig.4. Signal generator is connected to port 1. Port 6 is the measurement port. Port 2 is there for the reference power from generator and ports 3, 4, 5 are used for the power measurement between the line lengths l_1 and l_2, that represent the distribution of q points around the unity circle by α_1 a α_2 angles. The attenuator consists of resistors R_1 and R_2 for the suitable distance of q points from the center of unity circle. If we assume some minimum angle difference α_{min} in the impedance plane, it can be easily written with the simplification $l_1=l_2$ that

$$\alpha_{max} = 180° - \frac{\alpha_{min}}{2} \quad . \tag{13}$$

When we neglect the dispersion, we can write for the working range of sixport the following

$$\frac{f_{max}}{f_{min}} = \frac{\alpha_{max}}{\alpha_{min}} = \frac{180° - \frac{\alpha_{min}}{2}}{\alpha_{min}} = \frac{180°}{\alpha_{min}} - \frac{1}{2} \quad . \tag{14}$$

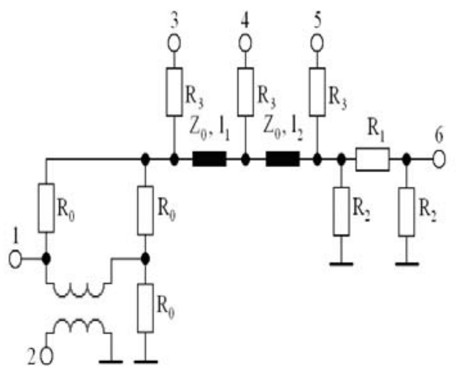


Fig.4 Schematics of the simplest sixport

The graphical representation of the equation (14) can be seen on Fig.8. There are two typical extreme values, for α_{min}=15° is the frequency range 1 : 11.5, on the other hand for α_{min}=120° the working range is 1 : 1, which means single frequency. Practical design can be seen somewhere between those extreme values depending of requirements on frequency range and measurement precision.

3 THE AIMS OF DISSERTATION THESIS

The aims of the work are following:

1. Detailed analysis of the main features of sixport and their influence on measurement abilities. The theoretical work should verify with practical experiments.
2. To propose the solution suitable to work as wideband measurement system with working range greater than one decade. The design should be proposed in such a way that it will be frequency independent and suitable to work on microwave frequencies.
3. To realize simple sixport system for the demonstration of main parameters, to verify the functionality of supporting circuits and computing PC software. Design the suitable calibration kit with sufficient frequency range.
4. To design wideband measurement system with the knowledge from the previous work and verify its behavior.
5. To make comparison of both systems and with available measurement systems.
6. To evaluate the designed measurement system parameters and the possibilities of realization for higher GHz frequencies.

3.1 DESIGN OF WIDEBAND SIXPORT

There are various ways in the search for fulfilling working requirements for wideband sixport. For the low frequencies, it is possible to build resistive bridges published in [6] or [9]. For the higher frequencies such a solution is not suitable. The straight way for the range increase can be the cascade connection of more sixports but they must be built in technology which ensures that signal will be transferred through them outside of their working range without excessive losses. Therefore the classical solutions built on waveguides are not suitable. If we choose the same $\alpha_{\min}$ for all sixports and the $f_{\max}$ of one sixport will be equal to $f_{\min}$ of the following, then we can expand the equation (14) to

$$\frac{f_{\max}}{f_{\min}} = \left(\frac{180°}{\alpha_{\min}} - \frac{1}{2} \right)^{h} , \qquad (15)$$

where h is the number of sixports in the cascade. The graphical representation can be seen in Fig.8 as black lines. There can be seen that for four sixport cascade and $\alpha_{\min}$=45° it is possible to get working frequency range greater than 1 : 100. For such a range we have to pay with the necessity of thirteen detectors (assuming only one reference detector for power from generator) and higher losses.

3.2 DESIGN OF THE NEW MEASUREMENT SYSTEM WITH THE SIXPORT PRINCIPLE

Previous chapter presented the possibility how to expand the frequency bandwidth with more sixports in the cascade. Main disadvantages of such method are implementation of three detectors for each frequency range, at each frequency we get only one result of measurement and with number of detectors the losses and unwanted reflections grow in the whole circuit.

The following text will propose the method, which minimize those disadvantages.

If we take a look at the Fig.5, the simplest improvement can be done by deleting one port between two sixports in cascade, because we get unnecessary identical signals from both ports. In such a way we can save one port per one connection between sixports. The measurement on the remained port will be used twice in the calibration and by measurement also. In the example in chapter 3.1 (4 sixports in cascade, working frequency range greater than 1 : 100) we can then reduce the number of used detectors from thirteen to ten.

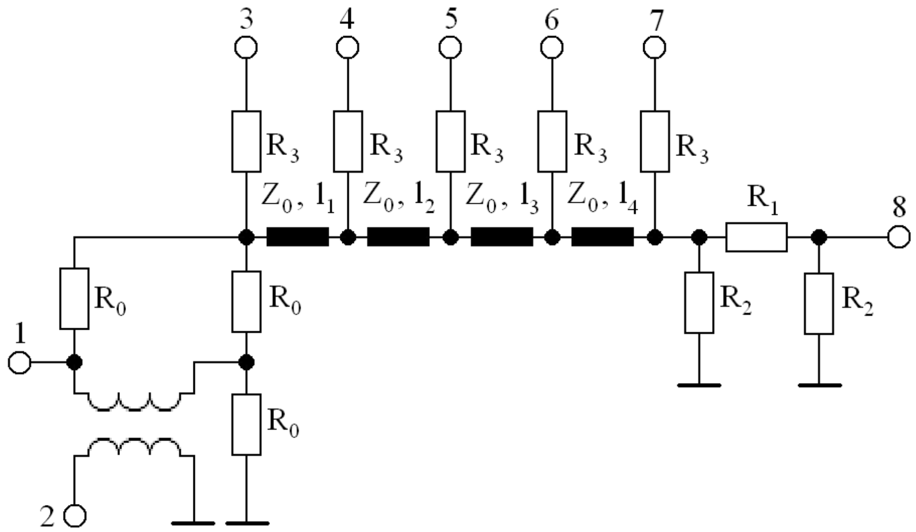


Fig.5 Schematics of reduced sixport cascade

When we look at the Fig.5, we can not distinguish boundaries of each sixport. It is then possible to generalize the circuit and to write, that for successful measurement on every frequency of operation there must be existing sixport fulfilling the requirements of $\alpha_{\min}$ and $\alpha_{\max}$ according to equation (14). The number of existing sixports in the circuit it is possible to compute from formula

$$C_m^3 = \frac{m!}{3!(m-3)!} = \frac{m!}{6(m-3)!} \quad , \qquad (15)$$

where m is the number of detectors in circuit for the phase measurement. Resulting numbers of sixports in the measurement system are then 4, 10, 20 and 35 for m 4, 5, 6 and 7 used detectors. Those results offer great potential for the design of modern measurement system.

3.3 THEORETICAL DESIGN OF MEASUREMENT SYSTEM

3.3.1 Creation of Goal Function

We were not successful with analytical description of behavior previously presented system. Therefore it was not possible to determine the lengths l_1, ..., l_{m-1} for the given parameters α_{min}, m detectors and required frequency range $f_{min} : f_{max}$. Another approach was used then and whole solution was searched numerically. The goal function is essential for the numerical method use and it describes the efficiency of the particular result to fulfill the input requirements. The comparison of more goal function results offer decision, which is better or worse. Further computation according to respective numerical method gives then next results with new goal function values. If we assume, that some set of values α_{min}, m, l_1,..., l_{m-1}, f_{min}, f_{max}, is known, at first, we can compute all sixports in the system with the use of (15). It is necessary then to evaluate the lengths of lines between respective detectors. For every sixport we must test whole range $f_{min} : f_{max}$ and find out, where it fulfills the α_{min} requirement. The first result is the set of frequencies, where the investigated sixport works. In the following Fig.6 is the frequency normalized with respect to f_{min} and α_1, α_2 correspond to l_1 a l_2 at this frequency. With the nondispersing line assumption we can see, that the working and non working frequency bands are periodical. The every sixport in the system must be investigated in the same way and then we can construct the function of valid sixports with respect to frequency of operation showed in Fig.6.

The function from Fig.6 must be transformed to goal function value. The most important features are counted with bigger significance, the other with smaller one. The following equation was proposed for the goal function computation

$$K = \sum_{\mathrm{i}=2}^{f_{\max}} \left(\frac{f_\mathrm{i} - f_{\mathrm{i-1}}}{f_{\mathrm{i-1}}} \cdot \frac{\left(n_{\mathrm{total}} - nval_{\mathrm{i-1}}\right)^{\mathrm{k}_1}}{n_{\mathrm{total}}} \right) + \mathrm{k}_2 \cdot \frac{f_{\max} - f_{\min}}{f_{\mathrm{last}}} + \mathrm{k}_3 \cdot \left(f_{\mathrm{last+1}} - f_{\mathrm{last}}\right) , \qquad (16)$$

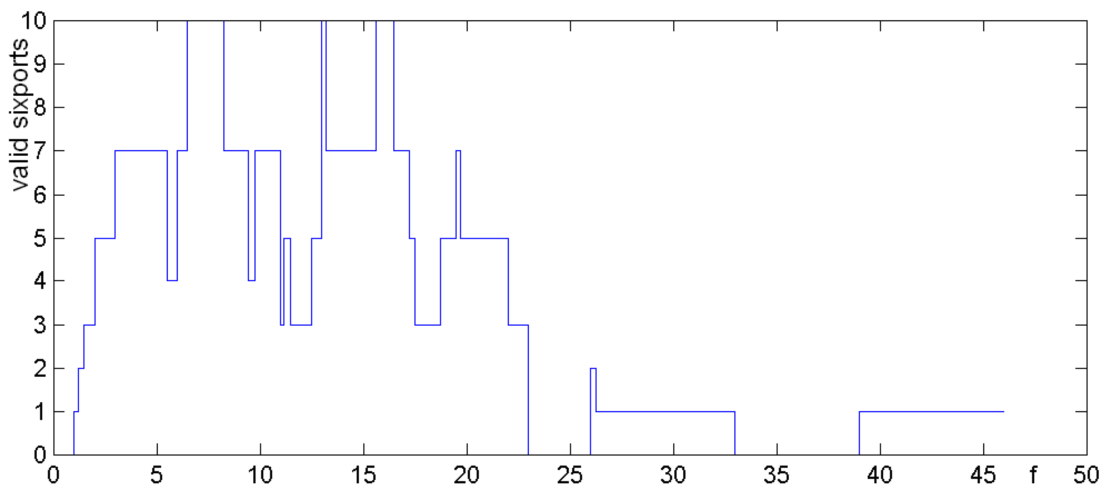


Fig.6 The frequency dependence of valid sixports for given parameters f_{min}=1, f_{max}=50, α_{min}=30°, α_1=25°, α_2=5°, α_3=10°, α_4=20°

where n_{total} is the whole number of the sixports in the design (15), $nval_i$ is the number of actually valid sixports in the respective frequency band, f_{last} is the first frequency at which there is no valid sixport in the circuit and f_{last+1} is the frequency, at which there is at least one valid sixport in the circuit again.

The first part of equation (16) express the circuit behavior in the frequency range. There are the numbers of valid sixports and their frequency ranges. Second part of equation (16) represents the obtained frequency range in the required one. The last part of equation expresses the first frequency band where there are no working sixports. The weighting coefficient values were determined experimentally as k_1=1, k_2=2 and k_3=0.1 for the case of maximum frequency range optimization.

3.3.2 On the Use of numerical Methods for the Measurement System Calculation

The numerical method selection depends on the type of goal function (16) available. Taking in the account, that both first and second derivations do not exist, it is not possible to use for the optimization the classical Newton methods. It is possible to use quasi-Newton methods, where the derivations are substituted by finite differences. Those methods have strong tendencies to find local minimums only, so they are suited for the refining on the previously known results. Method of steepest descent was programmed and used for such a reason.

Global methods are more suited for the search through whole space of results. Genetic algorithm is the one of the best known. This method was implemented with its typical operations as crossover, mutations and elitism. After selection of right weighting coefficients for each operation in this case, it is possible to obtain the results effectively and much better, than the results obtained by method of steepest descent. It was found experimentally, that the method is working even with small population. In that case, it is possible to obtain the normalized frequency f_{last} up to 120. From that, it can be seen, that it is possible to find the values of α_1 to α_4 for successful measurement system in the frequency range 1 : 120.

Even if the genetic algorithm was successful, other possibilities for computation of results were searched, because in the case of small values of α_{min}<30° and greater number of unknowns α the genetic algorithm optimization was very time consuming with computation times of several hours.

The particle swarm optimization algorithm is one of the modern methods [11]. It consists of random production of first generation, local and global minimum search, computation of each individual speed and direction. The algorithm works in the loop for given number of generations. The found minimums are more preferred in comparison with genetic algorithm and there is no necessity to do conversions of individuals to binary representations. The typical behavior can be seen in Fig. 7.

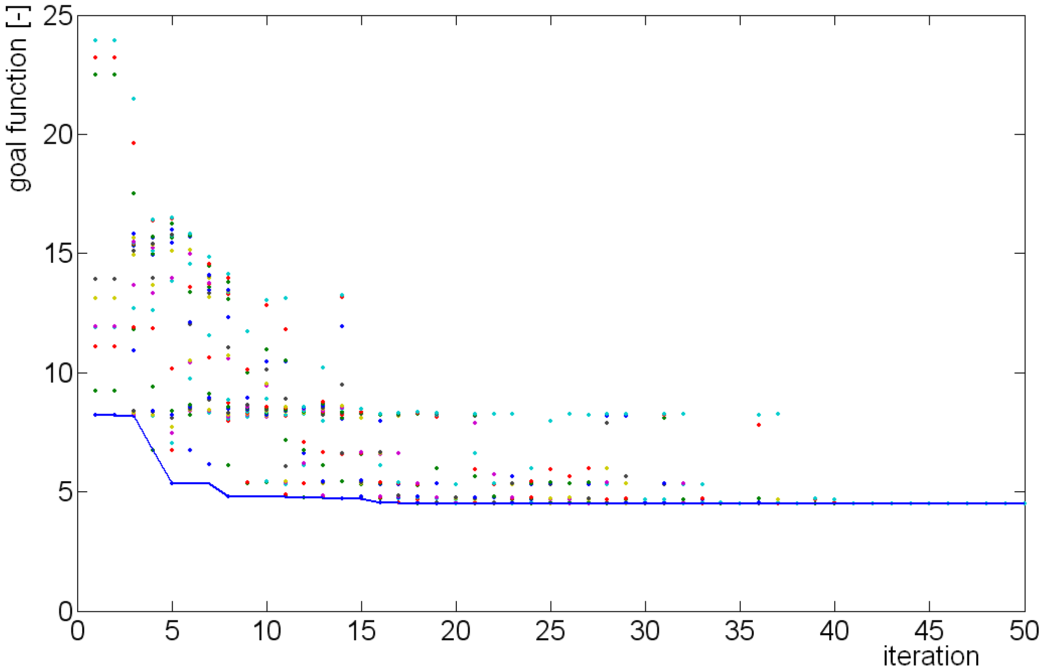


Fig.7 The optimization behavior of particle swarm algorithm with input values f_{min}=1, f_{max}=150, α_{min}=30°, 4 unknowns α_1 to α_4, 50 individuals in generation and 50 generations. Best 25 individuals of each generation displayed.

We can take the working frequency ranges of simple sixport and its cascades as reference plot. Then it is possible to put there the results of the numerical methods for a comparison as can be seen in Fig. 8. The optimizations were done subsequently for different α_{min} and various numbers of detectors in the measurement system. The optimizations were fast for the bigger α_{min} and smaller number of detectors. The computation of solutions for six and seven detectors in the system and smaller values of α_{min} took several hours. It was necessary to do the computation for the given input parameters more times, because of the use of random numbers in both algorithms, typically ten times. The construction of the Fig.8 was therefore very time and computation consuming. The particle swarm algorithm was more successful in the majority of cases and it has found better results with greater working range. It is clearly visible from the Fig.8 that results for the working ranges 1 : 100 and greater were found probably as local minimums only and their values are not following the trends from other computed results.

In the Fig.8 can be seen the comparison between sixport cascades and proposed measurement system. The cascade of three sixports (eight detectors) has the same frequency range as the measurement system with four lines and six detectors. In that way it is possible to save two detectors and moreover it offers twenty sixports at one frequency which means twenty measurement results at one frequency.

It is necessary to select required angle α_{min} for the measurement system design on the horizontal axis of Fig.8 and required frequency range on vertical axis. In the intersection or further from the plot origin can be found the suitable configuration of measurement system fulfilling the input parameters. There are now enough input parameters for the optimization to get the physical solution of measurement system for its construction.

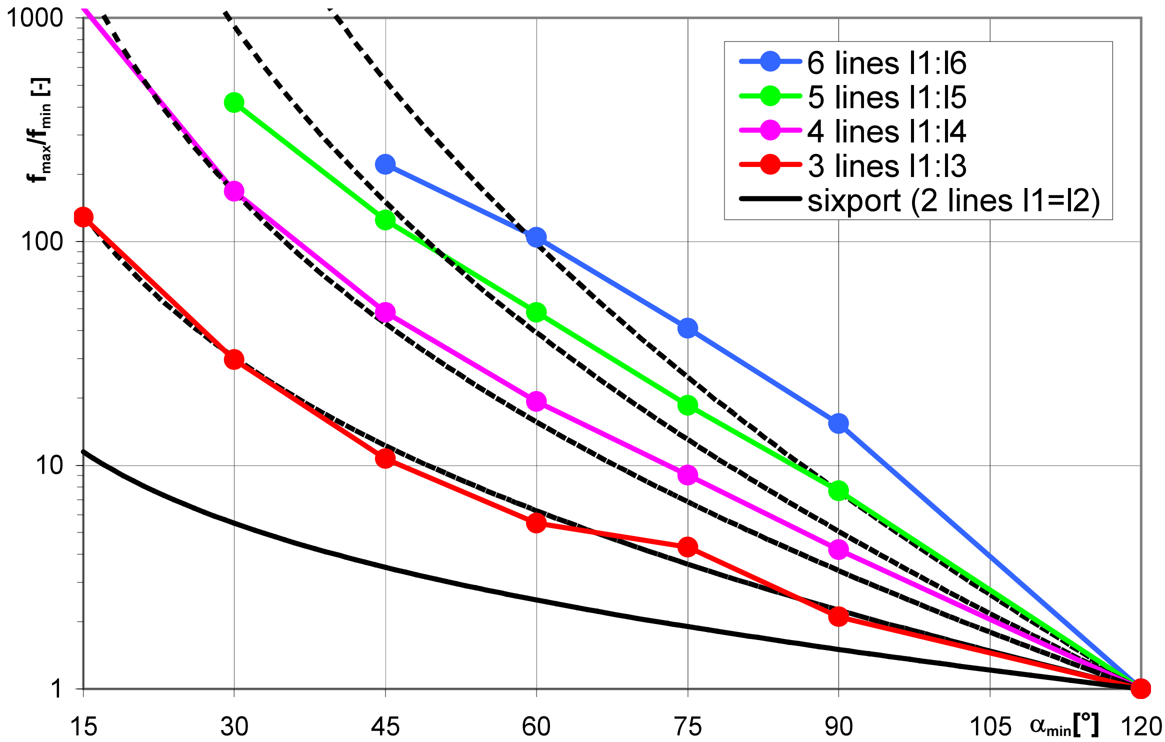


Fig.8 The working range of measurement system with respect to given α_{min}, where the parameter is the number of unknowns l_1 to l_{m-1}, optimized with particle swarm algorithm. Simple sixport is black solid line, cascades of two to five sixports are black dashed lines.

3.4 REALIZATION OF SIMPLE MEASUREMENT SYSTEM BASED ON SIXPORT METHOD PRINCIPLE

At first, the simple sixport measurement system was designed and built for gaining the experience and testing of all necessary blocks of the design. Fig.9 shows block diagram, where each part will be discussed later in detail.

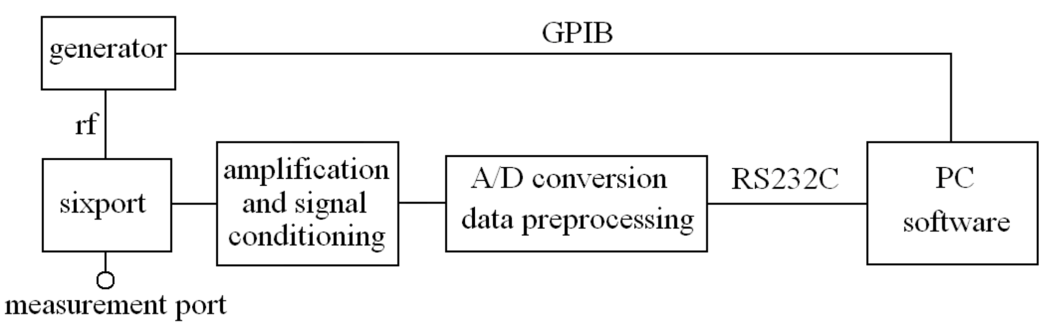


Fig.9 Block diagram of the measurement system

The main part of the measurement system is the sixport enabling impedance measurement. Principal circuit diagram is identical to Fig.5 but with four detectors only. Sixport consists of following building blocks, which must be properly designed: **resistive bridge, diode detectors, inserted lines and inserted attenuator**.

The detailed design of bridge and detector was realized first to obtain practical parameters. The parameters were optimized for maximum frequency bandwidth, after that the obtained frequency bandwidth was from 5 MHz to 3 GHz. The inserted lines can be easily designed as microstrip lines with characteristic impedance of 50 Ω taking into the account parameters of used material FR4. With the use of equations from literature, or by computation in freeware software Appcad, it is possible to solve the line width 1.55 mm and velocity factor ξ=0.562 for 1 GHz frequency. The length of the microstrip line can be defined as half of the minimum electrical length. By choosing $f_{\min}$=100 MHz and $\alpha_{\min}$=15°

$$l = \frac{c}{f_{\min}} \cdot \frac{0.5 \cdot \alpha_{\min}}{360°} \cdot \xi = \frac{2.997 \cdot 10^8}{100 \cdot 10^6} \cdot \frac{0.5 \cdot 15°}{360°} \cdot 0.562 = 0.0351\ \mathrm{m}\ . \tag{17}$$

According to equation (14) it is possible then to compute the following

$$f_{\max} = \left(\frac{180°}{\alpha_{\min}} - \frac{1}{2} \right) \cdot f_{\min} = \left(\frac{180°}{15°} - \frac{1}{2} \right) \cdot 100 \cdot 10^6 = 1150\ \mathrm{MHz}\ . \tag{18}$$

At last it is necessary to choose the value of inserted attenuation. From the Fig.3 and from following discussion it is clear, that suitable value of loss L is around 1.6 dB. From the equations for the π attenuator we have got: R_1=8.2 Ω, R_2=560 Ω.

Block for amplification and signal conditioning performs more functions, which result from the detectors parameters used in the sixport and from the used A/D converter at output.

The diode detectors have high output impedance, output voltage consists of bias and detected voltage, which subtracts from the first. The detector voltages range is between 200 mV and 0 mV. The output of the block feeds internal A/D converter of Cygnal (now Silabs) microprocessor C8051F020 with input range 0 to 2.43 V. The following parameters are required. For each measurement channel from sixport it is necessary to have one amplifying stage, bias subtraction and polarity change of detected voltage. All of these requirements can be fulfilled by one differential amplifier where noninverting input is connected to reference detector and inverting input to measuring detector. The selection of amplifier used must take into account temperature drift and offset smaller than one step of following A/D converter, which is circa 0.6 mV and after transformation of that value back to input of amplifier we get the error requirement of less than 50 μV. Such parameters fulfill only special operational amplifiers with zero drift and offset for example AD8551 from Analog Devices.

The A/D converter has as the inputs the amplified voltages from detectors in range 0 - 2.43 V in eight channels maximally. The control is done through RS232C. Converted data sent through serial line to PC are output of the block. It is realized with the use of evaluation kit for

C8051F020. It has MCS51 compatible core and other peripherals, from which is used the twelve bit eight channel A/D converter.

The PC software was always meant as demonstrational. All the software was created in development environment Agilent VEE Pro. This offers fully graphical programming with building blocks offering communication, data handling, visualization, control and many others. Program is divided to five parts which logically differ in function and type of use.

First main part only calls the other specialized blocks and visualize them. User of the program after start sees only selected functions on so called panel.

Communication setting part offers the selection of configuration parameters for A/D converter and microprocessor. There is also the possibility to read calibration data from file.

In the calibration of detectors part, the detectors in the particular sixports need to be calibrated due to various influences from design, temperature, bias voltage etc. At first the software measures levels at every channel without the presence of RF signal, whose are the residuals of bias voltage. Then program controls with the use of GPIB signal generator and sweeps its output power at given frequency. The channel levels are measured with A/D at each power step. The approximation of measured points is done with polynomial of sixth or higher order, which can be selected. The error of approximation is typically below 0.005 dB, but precision of internal attenuator in generator limits the calibration practically. Other possibilities of calibration are described in literature, where in particular cases is the identified error smaller than 0.02 dB.

The selection of calibration set and its design is described in the dissertation work. The simplest method for calibration of sixport was selected according to definition by equation (4) and its transcription as (5) and (6). According to them, it is possible to compose the set of fourteen linear equations with eleven unknowns, where P_{ik} means power at i-th detector for k-th load, k=1 to 7

$$F_1 P_{1k} + F_2 P_{2k} + F_3 P_{3k} + F_4 P_{4k} - r_k H_1 P_{1k} - r_k H_2 P_{2k} - r_k H_3 P_{3k} + 0 + 0 + 0 + 0 = r_k P_{4k}, \qquad (19)$$

$$0 + 0 + 0 + 0 - x_k H_1 P_{1k} - x_k H_2 P_{2k} - x_k H_3 P_{3k} + G_1 P_{1k} + G_2 P_{2k} + G_3 P_{3k} + G_4 P_{4k} = x_k P_{4k}. \qquad (20)$$

The solution of the set of equation is realized as external function calling written in Matlab, which is fully supported in VEE environment.

For the practical calibration it is necessary to have the S parameters of calibration set for the required frequency range and step. The measurement of detector levels for the calibration set in required frequency range follows. From the previous calibration of detectors, levels of A/D converter are transferred to equivalent powers. After pairing of all files with known parameters for calibration set and measured powers from the sixport, the actual computation of calibration constants can be executed.

Measurement itself consists of various measurements visualizations. There are measurement of levels from A/D converter, measurement of powers from detectors in sixport and typical results measurements as return loss amplitude and phase of unknown load, measurement of real and imaginary part of load impedance and its representation in the Smith chart.

The impedance of the load in the case of the last three measurements is computed with the use of calibration constants previously computed and saved to disc. The following Fig.10 and Fig.11 show practical results of some measurements of load. It can be seen from them, that working frequency range is between 170MHz and 950MHz which represents bandwidth circa 1 : 5.3. It is necessary to understand, that measurements will be so precise, as the measurement of calibration set. Every error is transferred to measurement itself.

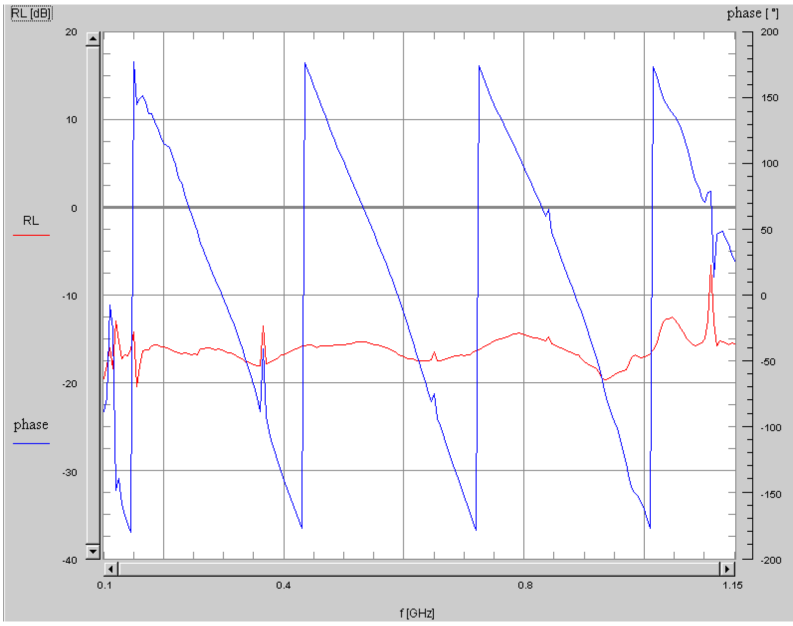


Fig.10 Measurement of return loss amplitude and phase for load 36 cm coaxial line and 68Ω.

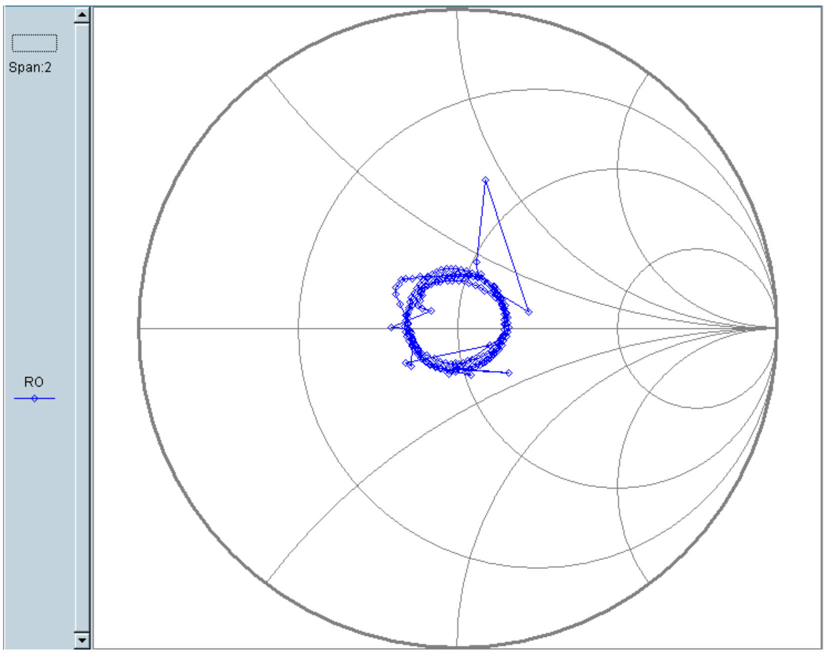


Fig.11 Measurement of return loss for load 36 cm coaxial line and 68Ω in Smith chart.

3.5 MEASUREMENT RESULTS WITH SIMPLE SIXPORT SYSTEM

The suitable load system was searched for thorough evaluation of designed sixport measurement parameters. The switchable attenuator HP 8494B with range 0 - 11dB ended with short was selected. The attenuator is specified for frequency range up to 18 GHz and in this case is not so important the actual value of attenuation but its repeatability, which is specified to be better than 0.01 dB. The attenuator is connected to measurement system with coaxial line of 26 cm length, which allows phase change big enough with respect to frequency. For the smaller return loss testing there was inserted additional fixed attenuator PE 7005-10 with 10 dB attenuation between the coaxial line and switchable attenuator. It allowed expanding the range of return loss down to level ~ -42 dB. Lower values of return loss are unattainable with this method, because then the reflections from input of attenuators exceeds the wanted ones from the short.

For the attenuator setting levels 0, 2, 4 and 6 dB, the measurements with simple sixport measurement system in comparison to reference measurement of vector network analyzer Agilent E8364B show the earlier mentioned frequency band, where system measures with small error, here 150 MHz to 1 GHz. The deviation from reference values is under 0.5 dB in amplitude with the exception of three discrete frequencies, where the numerical method in calibration produced sign change in calibration constants and measurement there is inaccurate. The deviation from the reference values is under 2.5° in the phase with the same exceptions.

For the attenuator setting levels 8, 10, 12 and 14 dB, the measurements show, that the frequency range narrows between 200 MHz and 900 MHz. With the lowering return loss, the errors both in amplitude and phase grow, which is consistent with theoretical assumptions. The measured characteristics can be seen in full dissertation thesis.

It is possible to establish the main parameters of simple sixport measurement system from the previous measurements. The practical working frequency range is from 200 MHz to 900 MHz, which at lowest frequency corresponds with value α_{min}=30°. The precision of measurement can be evaluated by computation of standard deviation for measured loads. Such a characteristic can be viewed in Fig.18 with respect to amplitude of return loss. Light blue points correspond with measurements of calibration set and dark blue with the switchable attenuator for the frequency range 200 MHz to 900 MHz. The standard deviation for the range from 0 to -25 dB of return loss is quite stable and the values are given mainly with bigger errors on discrete frequencies discussed previously. If we choose frequency range without these errors, for example 580-900MHz, we get dark green points for calibration set and red one for switchable attenuator. Other curves in the Fig.18 show the resolution of design computed with (12) and repeatability of used attenuator. The important curve is the measurement uncertainty of VNA Agilent E8364B, which was used for all reference measurements. The standard deviation of the phase measurement was computed similarly and can be seen in Fig.19 for both bandwidths, calibration set and switchable attenuator. The phase measurement uncertainty of VNA Agilent E8364B can be seen there too.

3.6 REALIZATION OF WIDEBAND MEASUREMENT SYSTEM BASED ON SIXPORT METHOD

The obtained knowledge after building the simple sixport measurement system allowed building of a system, based on the theory described in chapters 3.2 and 3.3. Measurement system, realized in previous chapters, has the eight channel A/D converter. If we left one channel for generator sweeping signal measurement, we can use seven channels. One channel will be for reference power measurement from generator, so we have six channels for measurements on detectors along the line, this can be seen on Fig.13. As another modification the wideband directional bridge from Minicircuits TCD-18-4 is implemented. The main reason for the change was that it allowed for lower losses in the overall design.

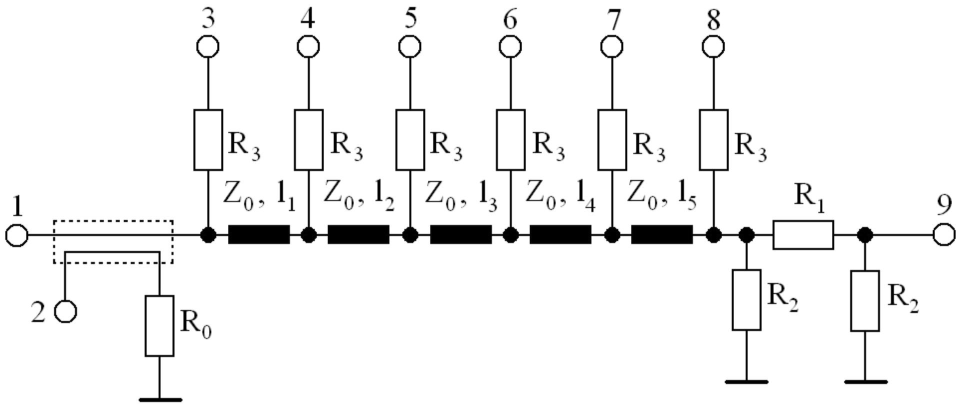


Fig.13 Schematics of the proposed wideband measurement system.

The diodes BAT 15-03W are used as detectors instead of the HSMS2822 used in simple sixport. The reason is that the former have more flat frequency response over the latter. The inserted attenuator was used identical to the simple sixport. The numerical methods used had set the seven detectors as its whole number in system.

The value α_{min} was selected along the results of simple sixport, where the bandwidth was determined as 1 : 4.5. From the Fig.8 can be found the corresponding value of α_{min}=36°. For the given number of detectors we can find in the same figure the attainable bandwidth of 1 : 250. Taking into the account the manufacturing tolerances and practical lengths of lines on PCB, more conservative value of α_{min}=60° was selected. This choice offers the frequency bandwidth greater than 1 : 50. The computed values from the particle swarm optimization for the electrical lengths of lines are: $\boldsymbol{\alpha_1}$**=39.160°,** $\boldsymbol{\alpha_2}$**=22.822°,** $\boldsymbol{\alpha_3}$**=7.830°,** $\boldsymbol{\alpha_4}$**=6.139°,** $\boldsymbol{\alpha_5}$**=50.529°**.

The resulting bandwidth of that particular set was computed as 1 : 53.63. The physical lengths can be computed with the use of selection f_{min}=50 MHz and equation (17) as $\boldsymbol{l_1}$**=183.2 mm,** $\boldsymbol{l_2}$**=106.8 mm,** $\boldsymbol{l_3}$**=36.6 mm,** $\boldsymbol{l_4}$**=28.7 mm,** $\boldsymbol{l_5}$**=236.4 mm.** The maximum working frequency is then f_{max}=2680MHz. The resulting frequency dependence of working sixports in the system can be seen in Fig.14. There can be seen, that we are getting more working sixports at each frequency, four in most cases and sometimes even eight and more. This would be used for precision improvement.

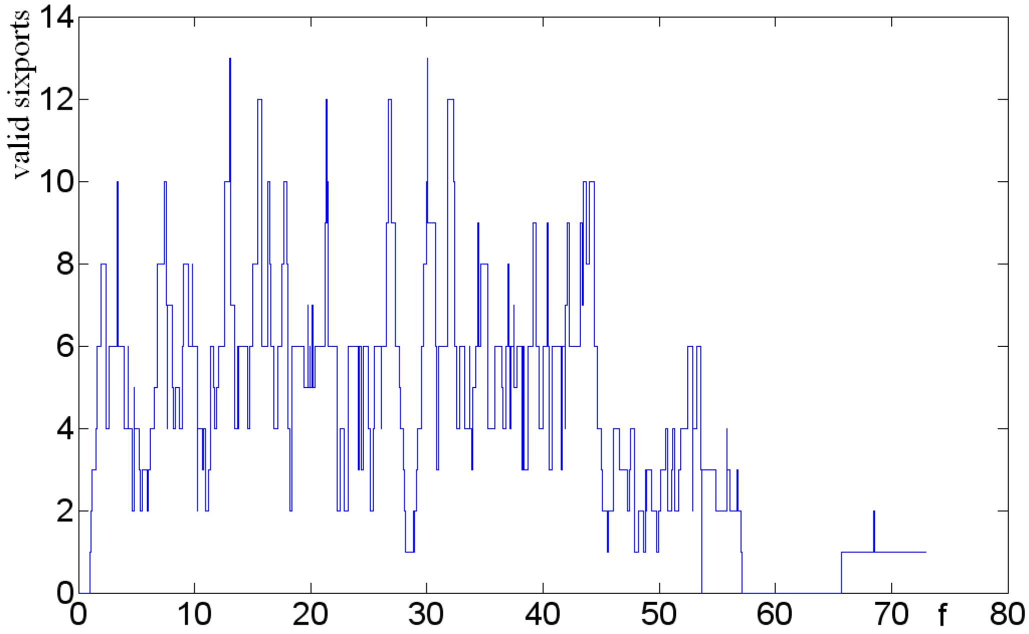


Fig.14 Frequency dependence of total number valid sixports in case α_{min}=60° and seven detectors.

Software described in chapter 3.4 is used for the detectors calibration. The calibration of the measurement system is done in the same way, as in the case of simple sixport, but with following extension. The system consists of twenty sixports, so after measurement of calibration set, the calibration constants for all sixports are computed. It is possible to identify frequencies, were is each sixport working from the numerical results obtained, but due to the experience in the case of simple sixport where even in the center of frequency range the results with great error were obtained, this was not implemented. In Fig.15 can be seen the measurement example of 8.2 Ω. The single points show the computed results from all of the sixports in the system and the red line is the reference measurement. It can be seen, that lot of results is incorrect, sometimes off tens of dB. There were researched ways to select the right results from the group of obtained ones.

The simplest method, which was tested, is the averaging, it the Fig.15 as blue line. The results were poor due to the use of the evidently wrong results. Better results were obtained with the use of median, showed in Fig.15 with the green line.

The best results were obtained with the following method. Selection of the results is based on the assumption that the majority of results is right, or close to the result. The output result is computed from the ten sixports selected only. The selection is done step by step. The average is computed from all results and the result furthermost from it is discarded. The process ends with defined number of sixports left and their results are then averaged. In Fig.16 can be seen the result computed from the subset of ten results from the twenty in the measurement system. The selection of the number then is based on the Fig.17, where there are results of measurement computed for various loads and range of subset sizes. There can be seen flat minimum around the value ten. The result is valid for this particular used measurement system of course.

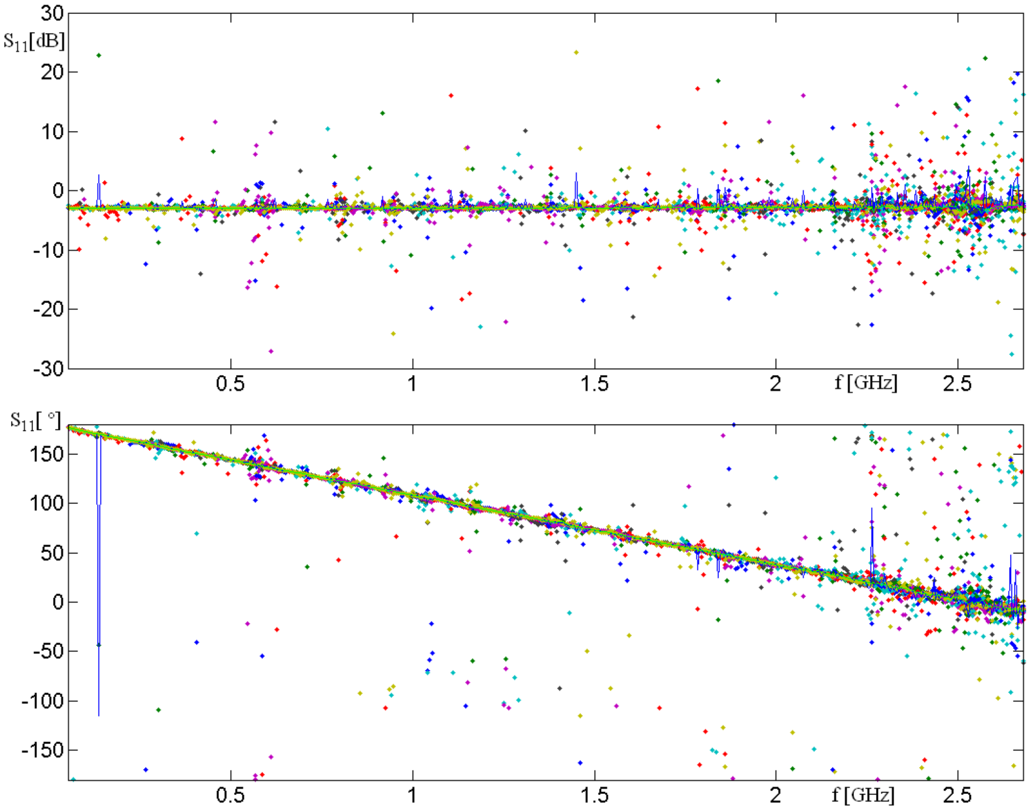


Fig.15 The 8.2 Ω load measurement with wideband measurement system, results of all sixports in the system, average – blue line, median – green.

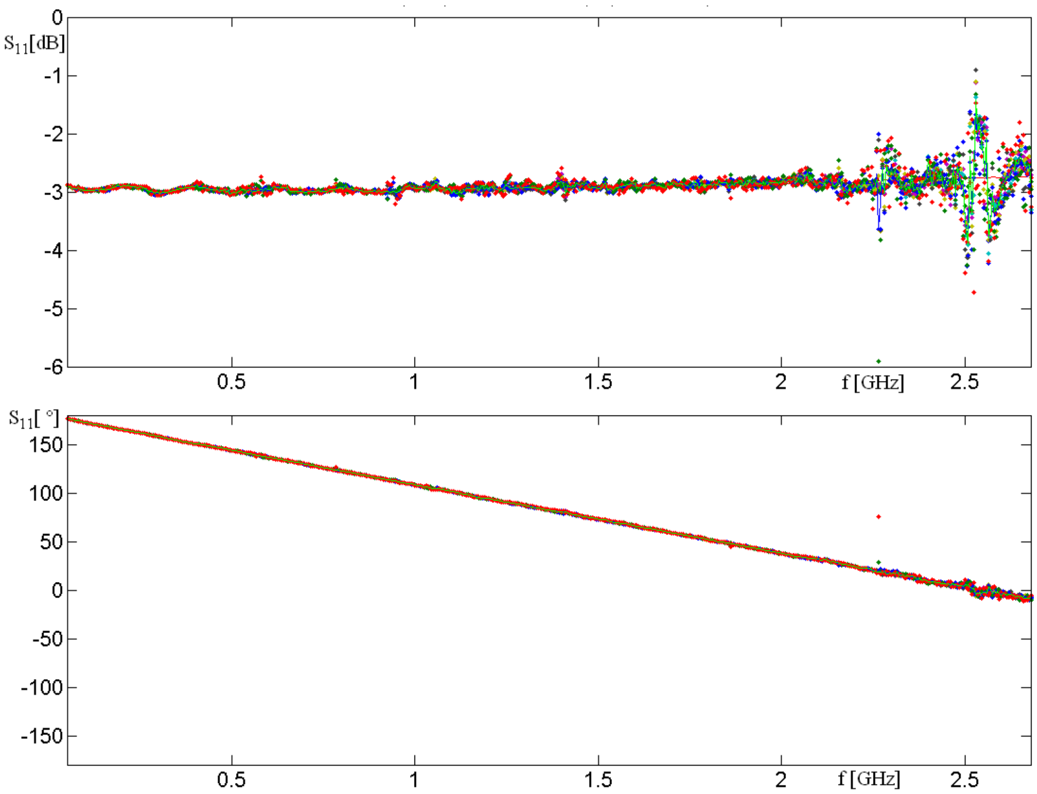


Fig.16 The 8.2 Ω load measurement with wideband measurement system, results of ten sixports in the system for each frequency.

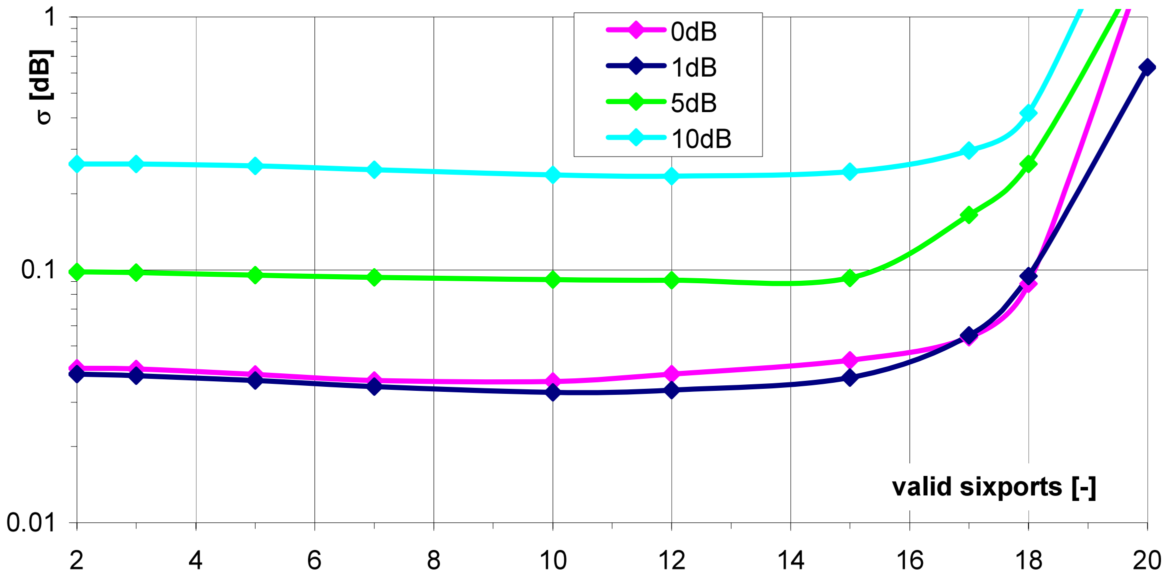


Fig.17 The dependence of measurement result standard deviation on number of sixports from which the result is computed, other results are discarded. The load is variable attenuator with short.

3.7 MEASUREMENT RESULTS WITH WIDEBAND SIXPORT SYSTEM

The evaluation of the measurement system was done the same way as in the case of simple sixport in chapter 3.5. The variable attenuator ended with short was used and measurements were compared to the reference ones obtained with the use of VNA E8364B.

The results for the attenuator setting values 0, 2, 4 and 6 dB show that system works in the whole designed range from 50 MHz to 2.68 GHz with the error in the range -1.4 to +0.7 dB. Error bigger than 0.3 dB can be seen on discrete frequencies above 2 GHz mainly. The only exception is the frequency 75 MHz, where the error goes to 1 dB. The reason of that error is not known yet. Investigated were both the calibration and reference measurements without success. The bigger error sizes above 2 GHz are due to the use of calibration set with unsuitable distribution in impedance plane and due to the lower detector sensitivity above this frequency. The phase error is within the -10° to +6° in the whole frequency range and the error is much smaller below 2 GHz within -2.5° and +1.5°.

The measurement results for the attenuator settings 8, 10, 12 and 14 dB show, that the measurement error is greater with frequency and it is growing rapidly above 2 GHz. The maximum amplitude error is 5 dB and phase error 20°.

In the case of wideband measurement system, the both errors in amplitude and phase grow with lower return loss according to theoretical analysis.

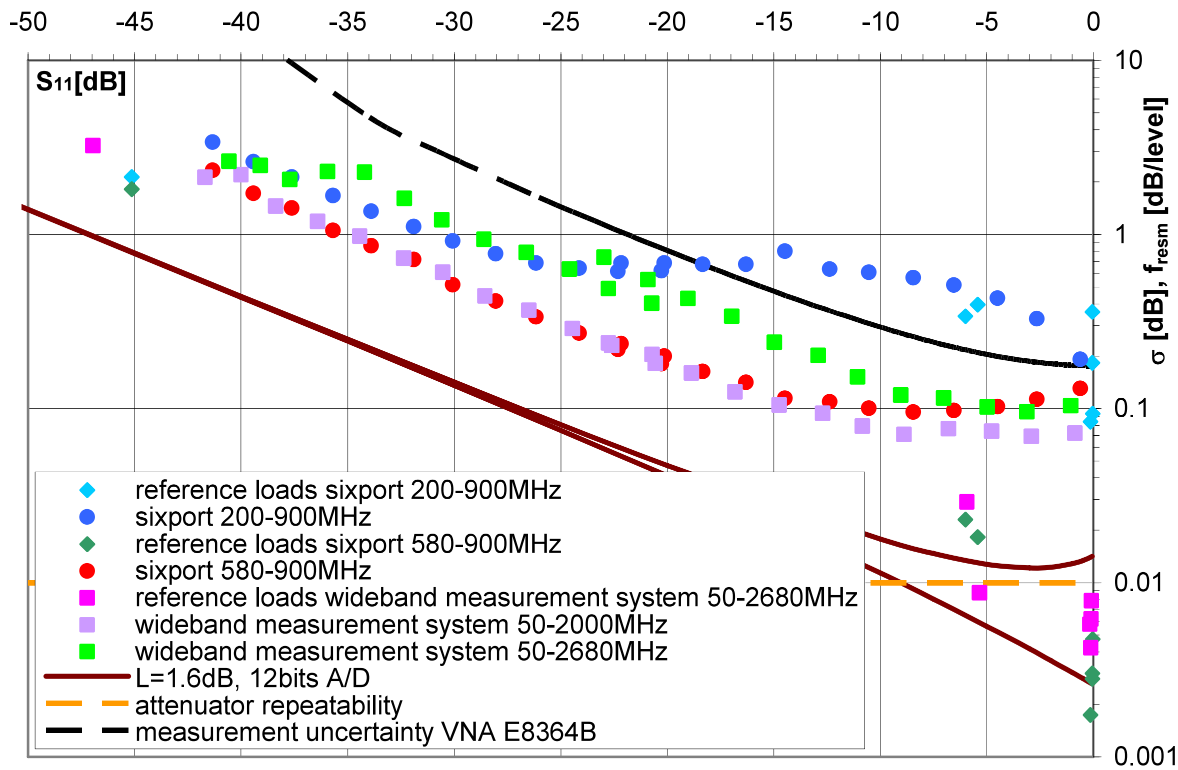


Fig.18 Return loss amplitude standard deviation vs. return loss value.

Fig.18 and Fig.19 show the summarized measurement results expressed by standard deviation of amplitude and phase measurement with respect to actual value of return loss. Figures show measurements of simple sixport in working and narrowed ranges and measurement of its calibration set. Then the maximum resolution of the used A/D converter can be seen there along with the repeatability of switchable attenuator used for evaluation measurements.

Separately the points computed for the wideband measurement system in working range 50-2680MHz and under 2 GHz only can be seen. It is clearly visible, that exclusion of the frequencies above 2GHz brings the lowering of standard deviation, which is in agreement with characteristics of measurement system described in the text. The narrowed frequency range of wideband measurement system offers lower of the same standard deviation as of simple sixport in narrow frequency band 580-900 MHz. The parameters of measurement do not suffer and in comparison with bandwidth 1 : 1.55, the bandwidth of presented system is circa 1 : 40 with the same precision. The last curve in the Fig.18 shows the measurement uncertainty of vector network analyzer Agilent E8364B which was used both for calibration set measurement and for evaluation measurement of switchable attenuator. There can be seen therefore the strong dependence of both realized systems results on precision of analyzer and obtained parameters of sixport measurement system can not be directly compared with the parameters of analyzer. With respect to obtained results there can only be said, that both realized measurement systems are not significantly worsening the parameters of analyzer. The whole standard deviation of measurement system or its precision should be computed with the repeatability of analyzer in mind. The similar thoughts can be expressed for the case of phase measurements in Fig.19 with the exception of switched attenuator where its repeatability in phase is not specified by manufacturer and maximum resolution of phase measurement was not deduced yet analytically.

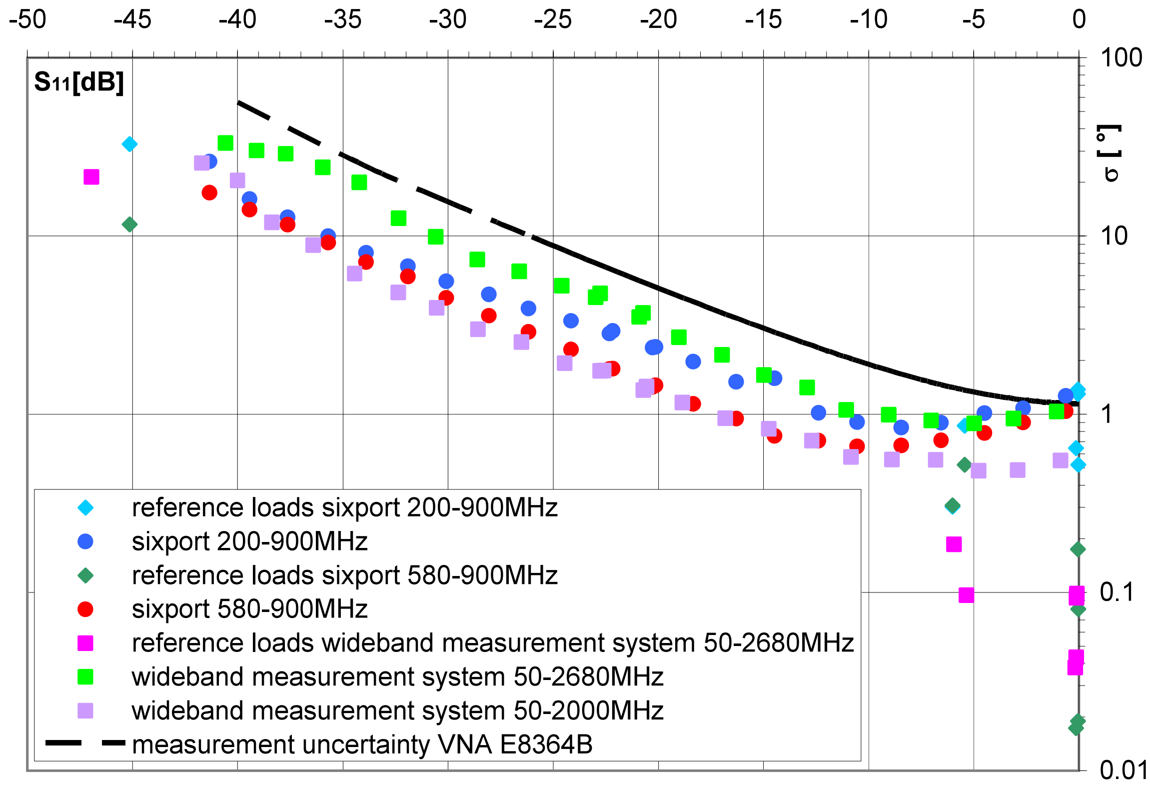


Fig.19 Return loss phase standard deviation vs. return loss value.

4 CONCLUSIONS

The overview of the microwave vector measurements was presented in the introduction of the work. Next the work focused on characteristics and potentialities of sixport measurement method which were partly taken from literature and some were originally deduced. The theoretical new method proposition of measurement, respective modification of sixport measurement system was described. The main parameters and advantages of the new presented system were shown, which are extremely wide bandwidth 1 : 100 and more in principle. The next advantage is the possibility of more results for one frequency obtaining, which can be easily used for the measurement error suppression or the precision enhancement.

The measurement system based on the simple sixport was designed in the practical part of the work. Its main purpose was to design the supporting circuits for signal conditioning and to write the software for PC. Even if the construction was trivial, the simple system worked in the frequency range 200 - 900 MHz, which equals to bandwidth 1 : 4.5. The measurement parameters were evaluated in the whole range and statistically treated to obtain standard deviation of output results. The return loss amplitude in range 0 to -30 dB has the standard deviation smaller than 0.8 dB, return loss phase has standard deviation smaller than 5°.

The most important part of the work is the design and realization of wideband measurement system based on sixport method, which is able by adding the additional detectors to simple sixport fundamentally expand the frequency bandwidth, in this particular example to 1 : 53.6 between frequencies 50 to 2680 MHz. The system theory is presented with possibilities of bandwidth greater than 1 : 1000. The next important feature of the presented system is the availability of multiple results for each frequency of measurement. In the realized system there was twenty results for each frequency and study of that example showed, that best measurement result can be obtained with the use of ten results out of twenty available. Simple selection method was described also. Practical measurements with the system showed that it works sufficiently in the entire designed bandwidth but at frequencies above 2 GHz has greater measurement error both in amplitude and in phase. Thorough research is showing that the reason is the used calibration set which was not designed for frequencies above 2 GHz. Wideband measurement system evaluation measurement shows in the frequency bandwidth 50 - 2000 MHz and in the return loss amplitude range 0 to -30 dB standard deviation smaller than 0.6 dB in amplitude and smaller than 4° in phase. In the return loss amplitude range 0 to -15 dB are those numbers even smaller, standard deviation 0.1 dB in amplitude and 0.9° in phase. Those results show the high measurement precision of realized system with wide frequency bandwidth 1 : 40.

The following work should be concentrated on measurement system realization which will work in the higher microwave frequencies. This is not principal problem because the described system is not frequency dependent and poses technology problem only for the realization of wideband enough detectors and resistive bridges. Signal conditioning and software is frequency independent and can be use immediately.

5 REFERENCES

[1] Hoffmann, K. and Škvor, Z.: A novel vector network analyzer. *MTT-S International Microwave Symposium Digest* 98.2 (1998 Vol. II [MWSYM]): 953-956.

[2] Golio M.: *The RF and Microwave Handbook.* CRC Press, New York, 2000, ISBN 0-8493-8592-X

[3] Engen, G. F.: Determination of Microwave Phase and Amplitude from Power Measurements. *IEEE Trans. Instrum. Meas.* , vol. IM-25, PP. 414-418, Dec. 1976.

[4] Collier, R.J. and El-Deeb, N.A.: On the Use of a Microstrip Three-Line System as a Six-Port Reflectometer. 1979 *Transactions on Microwave Theory and Techniques* 27. (Oct.1979 [T-MTT]): 847-853.

[5] Riblet, G.P., Hansson E.R.B.: The Use of a Matched Symmetrical Five-Port Junction to Make Six-Port Measurements. 1981 *MTT-S International Microwave Symposium Digest* 81.1 (1981 [MWSYM]): 151-153.

[6] Hesselbarth, J.; Wiedmann, F., Huyart, B.: Two New Six-Port Reflectometers Covering Very Large Bandwidths. *IEEE Transactions on Instrumentation and Measurement*,Vol. 46, No. 4, August 1997

[7] Engen, G. F., Hoer, C. A.: Application of arbitrary six-port Junction to power measurement problems. *IEEE Trans. Instrum. Meas.*, vol. IM-21, pp 470–474, Nov. 1972

[8] Somlo, P. I. and Hunter, J.D.: *Microwave Impedance Measurement.* Peter Peregrinus Ltd., England, 1985, ISBN 0-86341-033-2

[9] Bilík, V.,: Six-port Measurement Technique: Principles, Impact, Applications. Invited paper at the *International Conference RADIOELEKTRONIKA 2002*, [online], www.s-team.sk

[10] Bilík, V., Bezek, J., Rraffaj, V.: Three-probe X-band waveguide six-port reflectometer. *Elektrotechnicky casopis*, 1990, vol. 41, no. 5, p. 329-342 (in Slovak).

[11] Robinson, J., Rahmat-Samyi, Y.: Particle Swarm Optimisation in Electromagnetics. *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 2, February 2004

[12] Somlo, P. I., Hunter, J. D.: A Six-Port Reflectometer and its Complete Characterization by Convenient Calibration Procedures. *IEEE Trans.on MTT*, 1982, vol. MTT-30, pp.186-192.

6 SELECTED PUBLICATIONS

[13] Urbanec, T., Svačina, J.: Simple Six Port Measurement System Design. In *Proceedings of the 13th International Czech-Slovak Scientific Conference RADIOELEKTRONIKA 2003*. Brno, FEEC VUT Brno. 2003. p. 100 - 103.

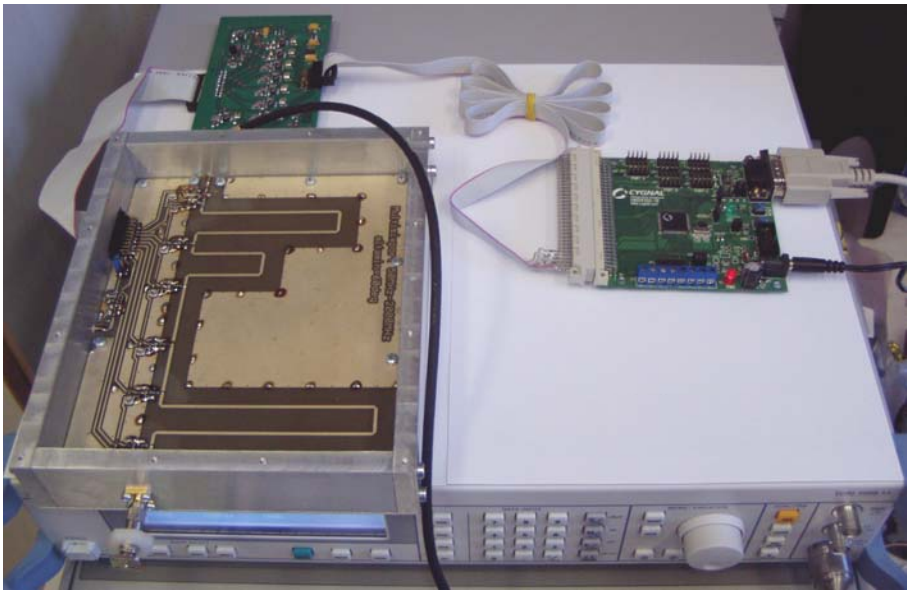
[14] Urbanec, T., Svačina, J.: Microwave Vector Measurements with Six-Port Technique. In *4th International Conference of PhD Students. Engineering Sciences I.* Miskolc, Hungary. 2003. p. 459 - 463. ISBN 963661590X.

[15] Urbanec, T., Svačina, J.: Software Support for Six-Port Measurement System. In *Measurement Science Review.* Journal of the Institute of Measurement Science, Slovak Academy of Sciences, 2004. 2004(4). p. 1 - 5. ISSN 1335-8871.

[16] Urbanec, T.: From Sixport to Multisixport Measurement Principle - Wideband VNA. In *Proceedings of 36th European Microwave Conference.* Manchester, Great Britain, European Microwave Association. 2006. p. 1563 - 1565. ISBN 2-9600551-6-0.

[17] Urbanec, T. Wideband VNA Design by the Multisixport Principle. In *Proceedings of the Sixteenth International Electrotechnical and computer Science Conference ERK 2007*. Ljubljana, Slovenia, Slovenia Section IEEE. 2007. p. 405 - 408. ISSN 1581-4572.

[18] Urbanec, T. Novel Approach for Wideband VNA by Sixport Principle. In *Proceedings of World Academy of Science, Engineering and Technology.* Venice, Italy, WASET. 2007. p. 30 - 33. ISSN 1307-6884.


Practical realization of the described wideband measurement system.

CURRICULUM VITAE

Ing. Tomáš Urbanec Ph.D., Nová 377, 683 35 Letonice, Czech Republic, status married,
phone +420 604 280 472, E-mail urbanec@feec.vutbr.cz, date of birth 7th June 1976

EDUCATION:

2000 – 2007 Brno University of Technology, Faculty of Electrical Engineering and Computer Science (from 1.1.2002 Faculty of Electrical Engineering and Communication), Ph.D. studies in the field of microwave vector measurements

1994 – 2000 Brno University of Technology, Faculty of Electrical Engineering and Computer Science MSc. study program Electronics and Communication

1990 – 1994 Grammar School of Nicholas Copernicus, Bílovec, aimed at mathematics

PROJECTS AND GRANTS:

2009 obtained grant „Modern Methods Evaluating Wideband Microwave Vector Measurements with Sixport Method“ supported by the Czech Science Foundation.

2006 obtained grant „Innovations of laboratory experiments in the course Special electronic parts and its applications“, supported by the Ministry of Education of the Czech Republic, Prague

2004 involved in the grant "Generation and scanning of electromagnetic field in measuring of effectiveness of shielding loss", supported by National Security Authority of the Czech Rep.

2004 Member of the Ph.D. student's team at the R&D project of the Grant Agency of the Czech Republic „Methods, structures and components of electronic wireless communication "

2003 obtained grant "Vector Measurements by Microwave Six-Port Method", supported by the Ministry of Education of the Czech Republic, Prague

2003 involved in the grant "Methodology of measuring the electromagnetic shielding effectiveness of small metallic boxes in area of low frequencies",National Security Authority of CR

2002 obtained grant "Design and Realization of Scalar Network Analyzer", supported by the Ministry of Education of the Czech Republic, Prague

2001 involved in the grant "Research of measurement methodology of TEMPEST and line filters", supported by National Security Authority of the Czech Republic, Prague

ABSTRAKT

V práci je popsán princip měření metodou šestibranu, jeho teoretický návrh, vliv jeho parametrů na přesnost měření a vlastnosti dalších obvodů pro zpracování jeho signálů. Jednoduchý šestibran byl plně realizován a jeho parametry prezentovány. Jako vlastní přínos je navržen nový přístup k použití metody s více detektory. Jeho základními vlastnostmi jsou více funkčních šestibranů na jednom pracovním kmitočtu a rozšíření pracovního pásma na rozsah 1 : 100 i více. Takový šestibran byl navržen pro rozsah 50 až 2680 MHz, realizován a jeho parametry prezentovány.

ABSTRACT

Theoretical principles of the sixport measurement method are presented. Description of theoretical design and influence of its parameters on measurement precision follows. Simple sixport measurement system was made and its parameters are described. As the main thesis contribution there is described a new approach to method with more detectors in the system. Mean features are more valid sixports at one specific frequency and frequency bandwidth available up to 1 : 100 and more. Such a wideband measurement system was designed for the frequencies between 50 and 2680 MHz and its parameters are presented in the work.

BIBLIOGRAFICKÁ CITACE DLE ČSN ISO 690

URBANEC, T. Speciální metody mikrovlnných vektorových měření . Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2008. Zkrácená verze Ph.D. Thesis. 32 s. Vedoucí disertační práce prof. Ing. Jiří Svačina, CSc.