Errors in Measurement of Microwave Interferograms Using Antenna Matrix

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Abstract. *New antenna matrices for both scalar and vector measurement of microwave interferograms for the frequency 2.45 GHz were developed and used for an analysis of sources of measurement errors. Influence of mutual coupling between individual antennas in an antenna matrix on a measurement of microwave interferograms, particularly on a measurement of interferogram minimum values, was studied. Simulations and measurements of interferograms, proposal of a new calibration procedure and correction method are presented. Influence of differences in radiation patterns of individual antennas of an antenna matrix on a measurement of microwave interferograms was studied as well.*

Keywords

Interferometry, microwave measurements, calibration.

1. Introduction

Microwave interferometry is being used in a number of industrial and medical applications such as antenna testing [1], testing of large civil mechanical and aerospace structures [2], medical applications [3], location systems [4], etc. From the measurement point of view, all these applications need to determine either amplitude or amplitude and phase of electric field intensity of an electromagnetic field distribution in a certain plane, area or even in space. The measurements can be realized either using some form of a single probe mechanically scanning system [2], [5], or using a number of switched transmitting and receiving antennas in tomography applications [3], or using some form of antenna matrices (AM), sometimes called microwave cameras [6]. The last solution has a great advantage in the possibility of fast real time measurements.

A great effort has been devoted to development of reconstruction algorithms for imaging of measured objects. Surprisingly, measurement errors and proper calibration are discussed sporadically.

In this paper, an investigation of measurement errors in both scalar and vector measurements of microwave interferograms using AM is described. Earlier developed AM [7], [8] were used for the study and two-wave microwave interferometry was considered.

2. Two-Wave Microwave Interferometry

A deformation measurement of a plain steel sheet can be used as an example of two-wave microwave interferometry. An object under test is illuminated by an electromagnetic wave radiated by a transmitting antenna. The wave reflected from the tested object interferes with a direct wave and creates an interferogram, see Fig. 1. In CST Microwave Studio interferograms on the frequency 2.45 GHz for both undeformed and deformed plain steel sheet (dimension 90 x 60 cm) were simulated. Interferograms were sampled with the step of 24 mm in both vertical and horizontal direction, see Fig. 2. There can be seen shifts of interference fringes with respect to the sheet deformation.

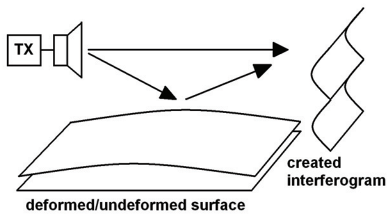

Fig. 1. Setup of the experiment for the scalar interferometric measurement of a deformation of a plain steel sheet.

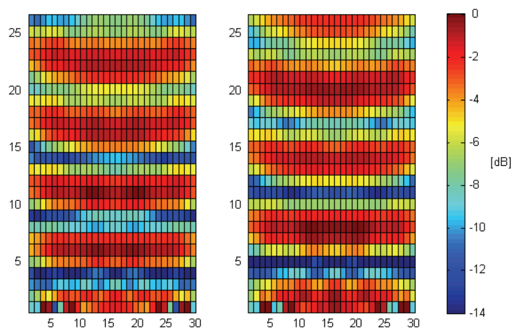

Fig. 2. Interferograms: plain steel sheet (left), deformed steel sheet, Δ = 50 mm (right). For the definition of the deformation Δ see Fig. 3.

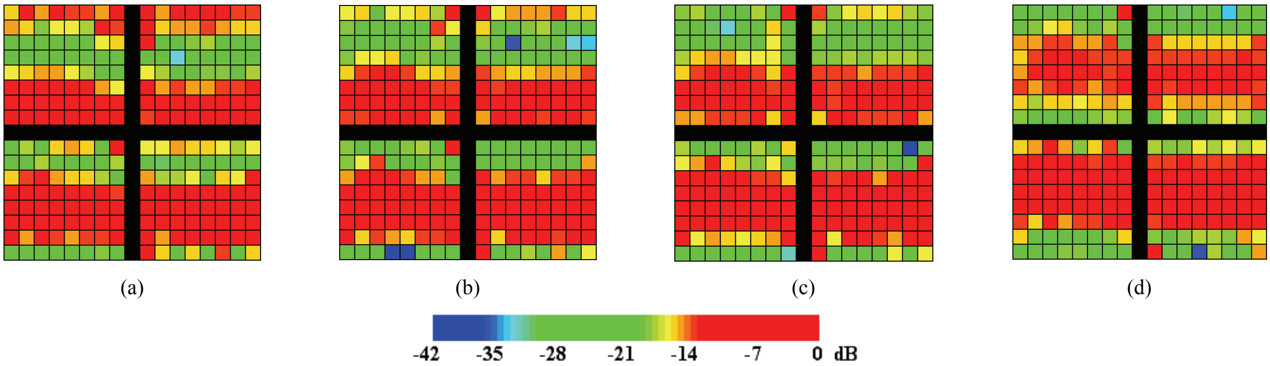

Fig. 3. Scalar interferometric measurement - experiment results at the frequency of 2.45 GHz. Amplitudes of the interferogram created by a plain steel sheet – without deformation (a) and with the deformation Δ = 15 mm (b), Δ = 21 mm (c), Δ = 42 mm (d). The deformation Δ is defined as a height of the center of the deformed steel sheet in comparison to the plain undeformed sheet.

3. Scalar Measurement of Interferograms

For the scalar measurement of microwave interferograms a scalar AM with 256 individual antennas for the frequency of 2.45 GHz was developed [7], see Fig. 4. Individual antennas are surface-mount ceramic antennas with dimensions of 5x8 mm, spacing between two particular antennas is 24 mm (approx. λ/5), both in vertical and horizontal directions. Individual antennas are connected directly to RF diode detectors, see Fig. 5. Detected voltages from individual antennas are measured by single A/D converter using a low-frequency multiplexer. All components are mounted on a single layer printed circuit board (FR4), which is fixed on a metal holder. The holder is covered by absorbers to minimize reflections from the AM.

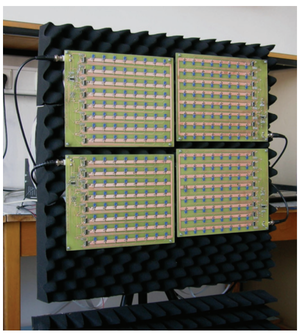

Fig. 4. Scalar antenna matrix (16x16 elements) - general view.

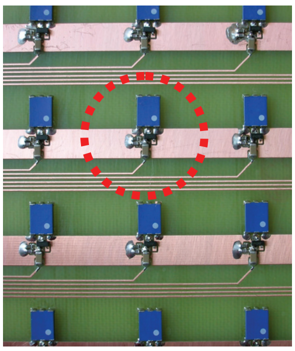

Fig. 5. Scalar antenna matrix (16x16 elements) - detailed view of a particular antenna with a RF diode detector.

Since SMD antennas are soldered directly to RF diode detectors, the only possible calibration of the system is to illuminate the scalar AM with a quasi-planar wave with variable amplitude.

With the scalar AM an experiment was performed: a shift of interferometric fringes for various deformations of a plain steel sheet (dimension 100 x 50 cm) was measured, see Fig. 3.

4. Vector Measurement of Interferograms

Design of the antenna matrix for the vector measurement of interferograms (vector AM) [8] comes from the AM for the scalar measurement [7]. The matrix consists of 64 individual SMD dipole antennas which are mechanically short but electrically half wavelength long and working at the frequency of 2.45 GHz, see Fig. 6 and Fig. 7. Individual antennas are spaced 29 mm (0.23λ) and they are mounted 100 mm above a metal holder, which is covered with an absorber. Individual antennas are connected to a 1:64 microwave switch. This microwave switch allows a measurement with a 2-port vector network analyzer (VNA) (Agilent PNA E8364A).

5. Measurement Errors and Their Correction

AM both for scalar and vector measurements were used to obtain data corresponding to real measurement arrangement. Data were analyzed and used for simulations to define measurement errors and their possible correction.

5.1 Measurement Errors Caused by Mutual Coupling between Individual Antennas

Since individual antennas in the AM are mounted as close to each other as possible, it was supposed that mutual coupling between individual antennas would occur.

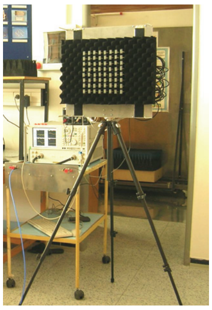

Fig. 6. Vector antenna matrix (8x8 elements) – general view.

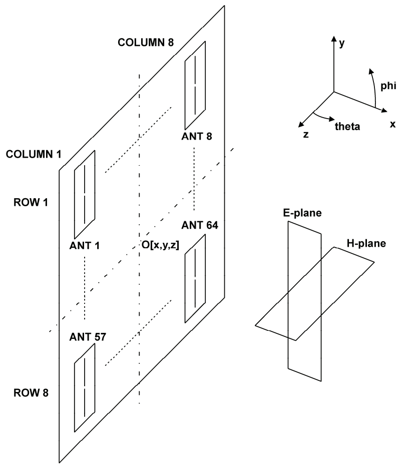

Fig. 7. Vector antenna matrix (8x8 elements) - indexing of individual antennas.

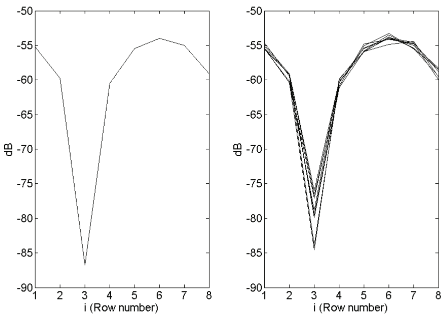

Fig. 8. Simulation - interferogram measured with the AM with no mutual coupling between individual antennas (left) and with mutual coupling - 8 various columns (right).

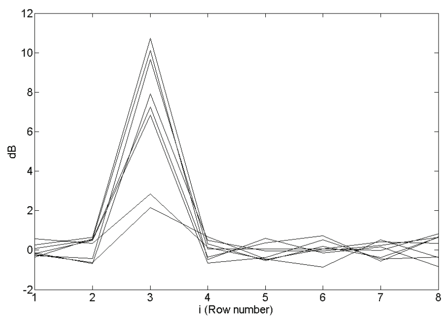

Fig. 9. Interferogram differences for simulated measurements based on properties of an ideal AM and properties of the realized and measured vector AM - 8 various columns.

Therefore this coupling between individual antennas was measured on the realized AM. The results were used for a simulation of measurement errors, see Fig. 8, Fig. 9. It can be seen that mutual coupling has strong influence on the measurement of minima of microwave interferograms causing measurement errors. In order to minimize these errors, a new calibration and correction method described in the following text was developed.

5.1.1 New Calibration/ Correction Method

Firstly, it is necessary to calibrate the microwave switch. An output of the microwave switch is connected to the port 2 of the calibrated VNA and the port 1 of the VNA is connected step by step to inputs 1 to 64 of the microwave switch. The transmission coefficient $A^{(i)}{}_{SWITCH,ON}$ and the reflection coefficient $\Gamma^{(i)}{}_{SWITCH,ON}$ of on-state and the reflection coefficient $\Gamma^{(i)}{}_{SWITCH,OFF}$ of off-state (an adjacent channel of the microwave switch is in on-state) of each channel of the microwave switch are measured (where i is the number of the channel of the microwave switch, i = 1..64).

Secondly, the AM is calibrated. The port 2 of VNA is connected to the output of the microwave switch. The port 1 of the VNA is connected step by step to individual antennas of the AM, all other antennas being connected to the switch. For each individual antenna, the reflection coefficient and the transmission coefficient to the other antennas of the AM are measured using the microwave switch. The result of this measurement is a 64 by 64 S-matrix $S_{ij}^{ANT,M}$ describing the AM and the microwave switch. For following simulations and measurements it is necessary to evaluate S_{ij}^{ANT} S-matrix describing solely properties of the AM. S_{ij}^{ANT} can be evaluated using formulas [9]

$$S_{ij}^{ANT} = \frac{S_{ij}^{ANT,M} A_{SWITCH,ON}^{(j)}}{D}, \tag{1}$$

for $i \neq j$ and

$$S_{ij}^{ANT} = \frac{S_{ij}^{ANT,M} A_{SWITCH,ON}^{(i)}}{D}, \tag{2}$$

for $i=j$ where

$$\begin{aligned} D = & \left(A_{SWITCH,ON}^{(j)} + \Gamma_{SWITCH,ON}^{(j)} S_{jj}^{ANT,M}\right) \\ & \left(A_{SWITCH,ON}^{(i)} + \Gamma_{SWITCH,ON}^{(i)} S_{ii}^{ANT,M}\right) \\ & - \Gamma_{SWITCH,ON}^{(i)} \Gamma_{SWITCH,ON}^{(j)} S_{ij}^{ANT,M} S_{ji}^{ANT,M}. \end{aligned} \tag{3}$$

From the real data in S_{ij}^{ANT} matrix, an error model covering mutual coupling between individual antennas was developed, see Fig. 10 (for indexing of individual antennas see Fig. 7). Significantly higher mutual couplings between individual antennas of the realized AM in vertical direction compared to mutual couplings in horizontal direction were measured. Therefore 4 adjacent antennas are considered in the vertical direction in contrast to the horizontal direction, where only 2 adjacent antennas are considered.

Due to mutual coupling between individual antennas the transmission coefficient P_i^M (which is equal to b_i) instead of P_i (see Fig. 10) is measured on the output of the i-th antenna

$$P_i^M = P_i + \frac{S_{i,i-1}^{ANT} P_{i-1} \Gamma_{SWITCH,OFF}^{(i-1)}}{1 - S_{i-1,i-1}^{ANT} \Gamma_{SWITCH,OFF}^{(i-1)}} + \frac{S_{i,i+1}^{ANT} P_{i+1} \Gamma_{SWITCH,OFF}^{(i+1)}}{1 - S_{i+1,i+1}^{ANT} \Gamma_{SWITCH,OFF}^{(i+1)}} + \frac{S_{i,i-8}^{ANT} P_{i-8} \Gamma_{SWITCH,OFF}^{(i-8)}}{1 - S_{i-8,i-8}^{ANT} \Gamma_{SWITCH,OFF}^{(i-8)}} + \frac{S_{i,i+8}^{ANT} P_{i+8} \Gamma_{SWITCH,OFF}^{(i+8)}}{1 - S_{i+8,i+8}^{ANT} \Gamma_{SWITCH,OFF}^{(i+8)}} + \frac{S_{i,i-16}^{ANT} P_{i-16} \Gamma_{SWITCH,OFF}^{(i-16)}}{1 - S_{i-16,i-16}^{ANT} \Gamma_{SWITCH,OFF}^{(i-16)}} + \frac{S_{i,i+16}^{ANT} P_{i+16} \Gamma_{SWITCH,OFF}^{(i+16)}}{1 - S_{i+16,i+16}^{ANT} \Gamma_{SWITCH,OFF}^{(i+16)}}. \quad (4)$$

This equation is based on generalized approach for phase interferometric measurements of electromagnetic field published in [10]. Mutual coupling between existing individual antennas are considered only.

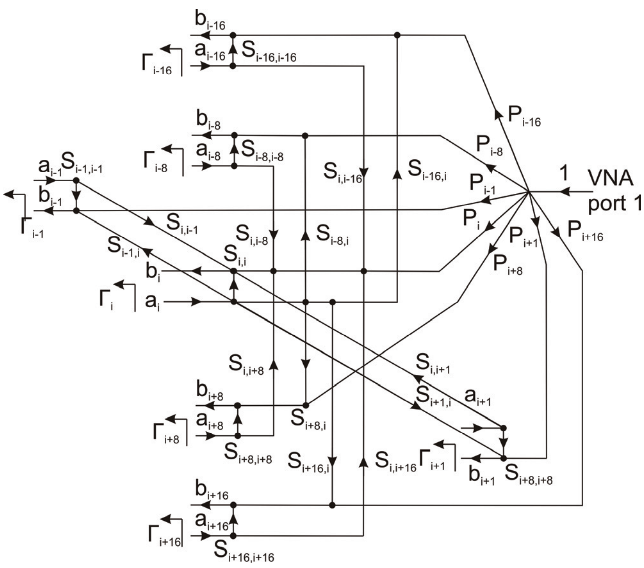

Fig. 10. Flow-graph – coupling effect between adjacent antennas. VNA port 2 connected to the i-th antenna.

The correction method for mutual coupling between individual antennas is based on the error model. To obtain the corrected values P_i instead of the measured values P_i^M it is necessary to solve linear system equations with 64 unknowns P_i and 64 equations based on (4).

To verify the impact of the correction method for mutual coupling between individual antennas on measurement results of interferogram minimum values, simple experiments were performed. Microwave interferograms were created with two horn antennas making angle 45 degrees (frequency 2.45 GHz). The setup of the experiments is shown in Fig. 11 – antennas making angle in x-y plane create interferometric fringes parallel to columns of the AM and antennas making angle in x-z plane create interferometric fringes parallel to rows of the AM.

The measured interferogram with interferometric fringes parallel to rows is displayed in Fig. 12 (8 various columns). The measured data were processed by the proposed correction method. The influence of the correction of mutual coupling can be seen in Fig. 13. Differences between measured and corrected data are summed up in Fig. 14.

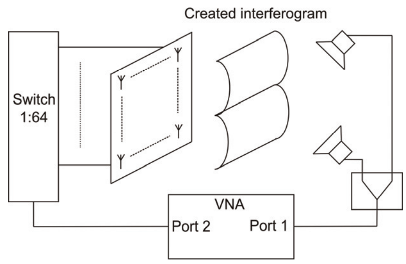

Fig. 11. Setup of the experiment.

The measured interferogram with interferometric fringes parallel to columns is displayed in Fig. 15 (8 various rows). The measured data were processed by the proposed correction method, see Fig. 16. Differences between measured and corrected data are summed up in Fig. 17.

In Fig. 14, the importance of the proposed calibration method is displayed. Difference between measured and corrected data in one column in a position of the minimum reaches the value of 18 dB. It can be seen in Fig. 13 that there is one sharp minimum and the other are flatter. It can be explained by assembly error in position of individual antennas.

If interferometric fringes are parallel to columns of the AM, differences between measured and corrected data are not so high in position of minima, see Fig. 17. It is caused by the construction of the AM – mutual coupling between individual antennas of the AM is higher in vertical dimension than in horizontal dimension.

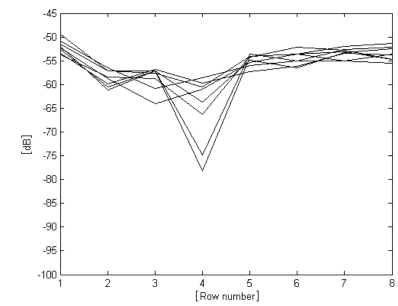

Fig. 12. Measured interferogram ($|P_i^M|$ values) – 8 various columns.

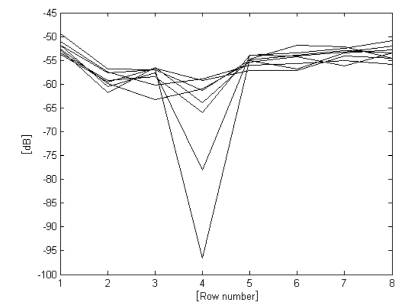

Fig. 13. Corrected measured interferogram ($|P_i|$ values) – 8 various columns.

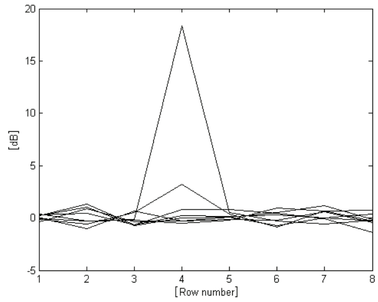

Fig. 14. Measurement error $|P_i^M|$-$|P_i|$ (8 various columns).

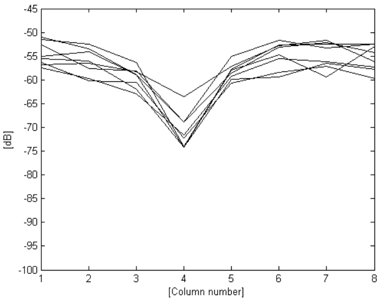

Fig. 15. Measured interferogram ($|P_i^M|$ values) – 8 various rows.

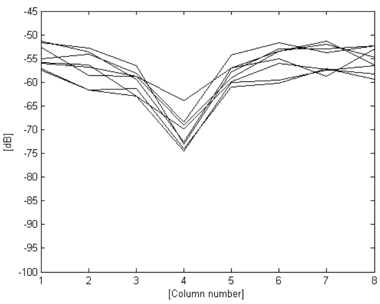

Fig. 16. Corrected measured interferogram ($|P_i|$ values) – 8 various rows.

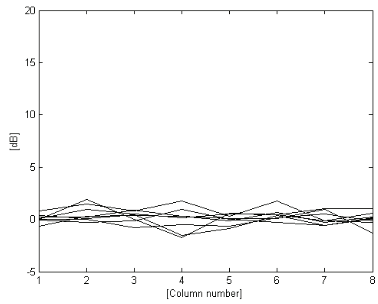

Fig. 17. Measurement error $|P_i^M|$-$|P_i|$ (8 various rows).

5.2 Measurement Error Caused by Differences in Radiation Patterns of Individual Antennas

In two-wave microwave interferometry, two electromagnetic waves come from two general directions. Intensity of the electromagnetic field in each point of the resulting interferogram is a function of phase shift between the two interfering waves and a function of amplitudes of the two interfering waves. The AM makes possible a correct interferogram measurement on the assumption that the AM is composed of identical individual antennas with identical half-spherical radiation pattern, the same resonant frequency and good matching. To verify validity of this assumption, extensive measurement of the realized AM was carried out.

Radiation patterns of all individual antennas in the AM were measured in anechoic antenna chamber in both E and H plane, see Fig. 7. All antennas except the measured one were terminated by internal 50Ω loads of the microwave switch. The measured results are displayed in Fig. 19 and Fig. 21. It can be seen that radiation patterns of individual antennas differ significantly and moreover they cannot be presumed half-spherical. In addition to this, some general differences between internal antennas of the AM and antennas on periphery of the AM were observed.

In order to clarify the problem a model of the AM composed of identical half wavelength dipole antennas was created in CST microwave studio. The simulation demonstrated that radiation pattern of individual identical antennas differs due to the presence of adjacent antennas in the AM, see Fig. 18 and Fig. 20.

It was also verified by measurement that resonant frequencies and radiation patterns of individual antennas differ due to fabrication tolerance which contributes to the complexity of the problem.

The influence of different radiation patterns of idividual antennas on measurement results were simulated using real measured data. A measurement of an interferogram with interferometric fringes parallel to rows with an ideal AM was simulated and used as a reference, see Fig. 22. Afterwards, the measured radiation patterns of individual antennas of the designed AM in E plane were implicated in simulated measurement, see Fig. 23. The influence of differences in radiation patterns of individual antennas of the AM is obvious and corresponds to the measured interferogram, see Fig. 24.

The same was done for a measurement of an interferogram with interferometric fringes parallel to columns and radiation patterns of individual antennas of the realized AM in H plane, see Fig. 25 and Fig. 26. The influence of differences in radiation patterns of individual antennas of the AM is obvious and matches the measured interferogram, see Fig. 27.

It can be said that differences in radiation patterns of individual antennas cause deformation of measured interferograms. Since two interfering waves could come from general directions, on the contrary to mutual coupling between individual antennas, there is probably no possible correction method to cancel this measurement error.

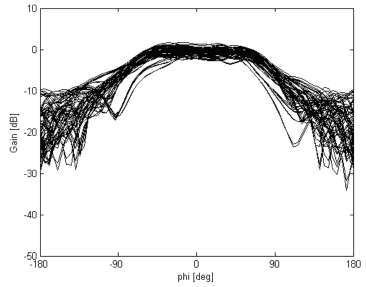

Fig. 18. Radiation patterns of all individual antennas in E plane in the vector antenna simulated in CST Microwave Studio.

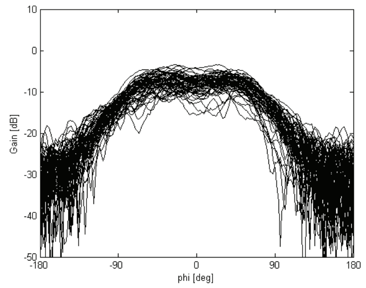

Fig. 19. Radiation patterns of all individual antennas in E plane measured in the vector AM using a microwave switch.

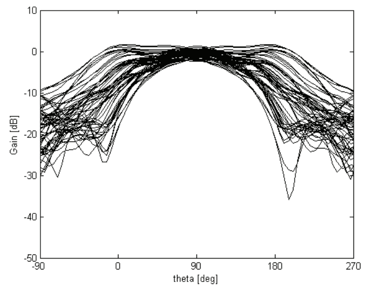

Fig. 20. Radiation patterns of all individual antennas in H plane in the vector antenna simulated in CST Microwave Studio.

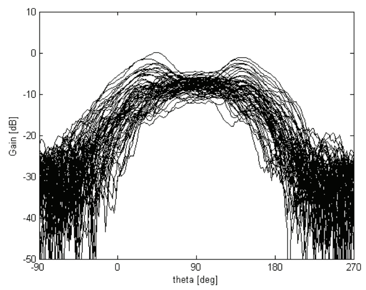

Fig. 21. Radiation patterns of all individual antennas in H plane measured in the vector AM using a microwave switch.

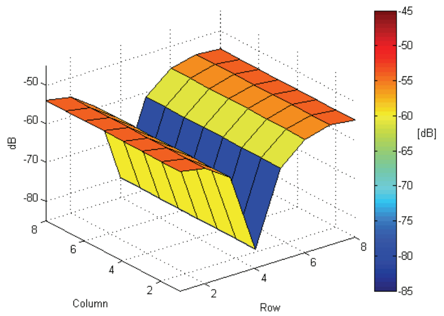

Fig. 22. Simulated measurement of an interferogram with interferometric fringes parallel to rows using the ideal AM.

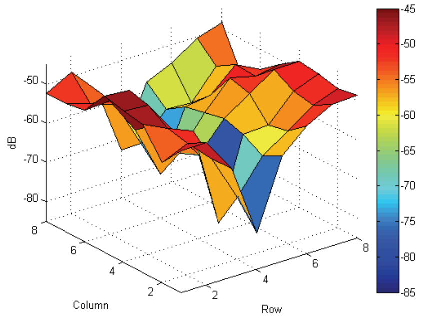

Fig. 23. Simulated measurement of an interferogram with interferometric fringes parallel to rows using the AM with real radiation patterns of individual antennas (E plane).

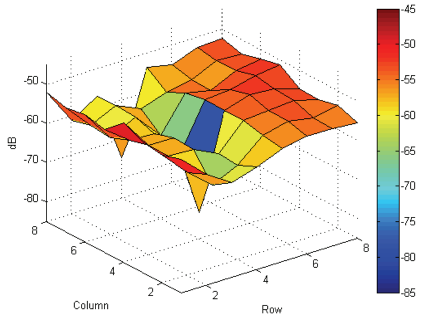

Fig. 24. Measurement of an interferogram with interferometric fringes parallel to rows measured using the real vector AM.

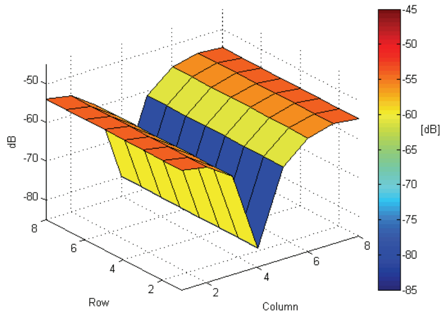

Fig. 25. Simulated measurement of an interferogram with interferometric fringes parallel to columns using the ideal AM.

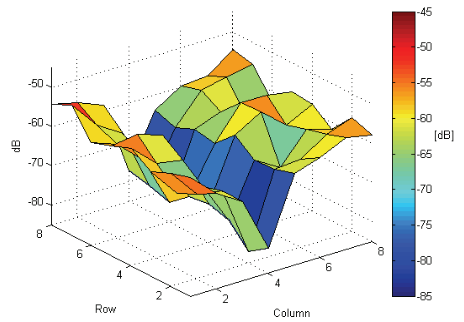

Fig. 26. Simulated measurement of an interferogram with interferometric fringes parallel to columns using the AM with real radiation patterns of individual antennas (H plane).

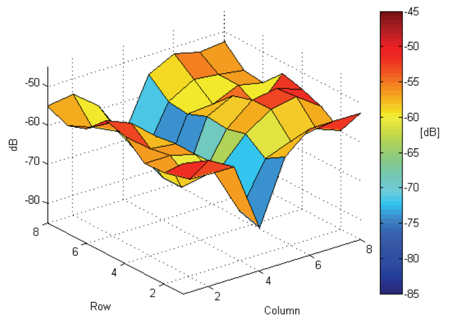

Fig. 27. Measurement of an interferogram with interferometric fringes parallel to columns measured using the real vector AM.

5.3 Discussion

From qualitative point of view, the above simulations and measurements show that there are many sources of errors in the measurement of microwave interferograms using both scalar and vector antenna matrix: differences in radiation patterns of all individual antennas in the antenna matrix due to presence of adjacent individual antennas, mutual coupling between individual antennas, different insertion loss and reflection coefficient of the microwave switch (vector AM) and differences in RF diode detectors (scalar AM). Next group of error sources is fabrication tolerance - various resonant frequencies and various radiation patterns of individual antennas of the antenna matrix, assembly tolerance, etc.

From quantitative point of view, errors in the measurement of microwave interferograms using both scalar and vector antenna matrix depend on realization of particular antenna matrix.

When using scalar AM, it is not possible to properly calibrate RF diode detectors (because RF diode detectors are calibrated with quasi-plane wave and radiation patterns of individual antennas are different). Also it is not possible to correct influence of mutual coupling between individual antennas. Since two waves come from general directions and there are differences in radiation patterns of all individual antennas, significant measurement errors occur and there is no possible calibration and correction method.

When using vector AM, it is possible to calibrate and correct mutual coupling between individual antennas, different insertion loss and reflection coefficient of the microwave switch. Error caused by differences in radiation patterns is identical to measurement with scalar AM (under the assumption that the setup of the experiment is identical).

To avoid measurement error caused by differences in radiation patterns of individual antennas, one-wave microwave interferometry should be suggested for measurement, see Fig. 28. Then two measurements are done (e.g. steel sheet with and without deformation) and changes in both amplitudes and phases are observed (there are no interferometric fringes). This type of measurement could be performed only with vector AM because both amplitudes and phases are measured. Since a wave comes from the same direction and measurement is comparative, differences in radiation patterns of all individual antennas in AM are not significant. This measurement method is being developed.

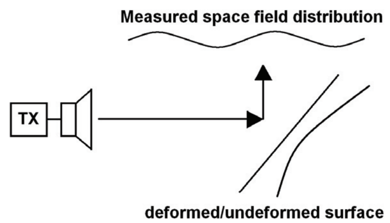

Fig. 28. Setup of the experiment for one-wave microwave interferometry.

6. Conclusion

An extensive analysis of error sources in scalar and vector measurement of microwave interferograms using antenna matrix was performed. Significant sources of measurement errors imposed by both fabrication imperfections and basic principles of measurement with antenna matrix were revealed. Comparison of scalar and vector measurement with antenna matrix with respect to measurement errors was performed.

A new correction method suppressing systematic measurement errors caused by mutual coupling between adjacent antennas was designed and experimentally verified.

New experimental arrangement "one-wave interferometry" was suggested. This arrangement should minimize errors arising from different radiation patterns of individual antennas of the antenna matrix.

Acknowledgements

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