VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

ÚSTAV RADIOELEKTRONIKY

Ing. Jan Puskely

RECONSTRUCTION OF THE ANTENNA NEAR-FIELD

REKONSTRUKCE BLÍZKÉHO POLE ANTÉN

DOCTORAL THESIS SHORT VERSION

Studijní obor: Elektronika a sdělovací technika

Školitel: doc. Ing. Zdeněk Nováček, CSc.

KLÍČOVÁ SLOVA

Blízké pole antén, rekonstrukce fáze, rovinné a válcové snímání blízkého pole, bezfázová měření, globální optimalizace, obrazové kompresní metody, Fourierův iterační algoritmus

KEYWORDS

Antenna near field, phase reconstruction, planar and cylindrical near-field scanning, phaseless near-field measurement, global optimizations, image compression methods, Fourier iterative algorithm

MÍSTO ULOŽENÍ PRÁCE / STORAGE PLACE OF WORK:

Ústav Radioelektroniky
Fakulta elektrotechniky a komunikačních technologií
Vysoké Učení Technické v Brně
Purkyňova 118
612 00 Brno

CONTENTS

1 INTRODUCTION

All today's wireless communication systems contain one key element, an antenna of some form. This antenna serves as the transducer between the controlled energy residing within the system and the radiated energy existing in free space. In order to satisfy the system requirements, a suitable antenna must be chosen and its performance must be evaluated.

The characterization of the antenna performance can be achieved by measurement in the near-field region or far-field region of the antenna. Information available from field measurements includes: far-field pattern, antenna gain, antenna directivity, axial ratio, beamwidth, phase center position etc. [1].

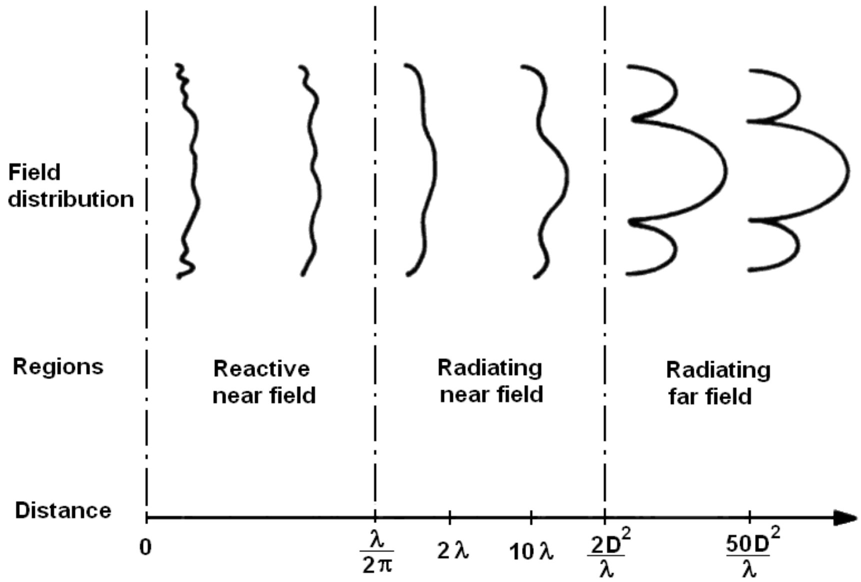

Fig. 1 Exterior fields of radiating antenna

Fig. 1 depicts the regions into which the exterior fields of a radiating antenna are commonly divided. The transitions between these regions are not distinct and changes between them are gradual [1][3].

The reactive near-field region is the region close to the antenna and up to about $\lambda/2\pi$ away from any radiating surface. λ is the wavelength. In the reactive region, the energy decays very rapidly with distance. In the radiating near-field region, the average energy density remains fairly constant at different distances from the antenna, although there are localized energy fluctuations.

The near-field test system measures the energy in the radiating near-field region and converts those measurements by a Fourier transform into the far-field result. The radiating near-field region extends from the reactive region boundary out to a distance defined as, $2D^2/\lambda$ with D being the largest dimension of the antenna aperture. The far-field region is beyond this distance where the angular distribution of the energy does not vary with distance, and the power level decays according to the inverse square law with distance.

2 NEAR-FIELD MEASUREMENT

Near-field measurements are used where large antennas are to be tested indoors in a relatively small space. This type of range uses a small RF probe antenna which is scanned over a surface surrounding the test antenna. During the measurement, near-field information is collected over a discrete matrix of points. This data is then transformed to the far-field using suitable techniques [1]. The resulting far-field data can then be displayed in the same formats as conventional far-field antenna measurements.

2.1 CONVENTIONAL MEASUREMENT METHODS

Standard measuring methods in the near-field assume scanning of the amplitude and phase of the electric field [1]-[3]. Measurement of antenna near-field is performed in the near-field region lying in the range of distances λ and $2D^2/\lambda$. Magnetic and electric field propagate almost with zero phase shifts in this region, as it is in a far field. The knowledge of the electric field will be considered for this reason.

Assume that the AUT radiates only into the right half-space and planar scanning area is located at defined distance from the AUT (Fig. 2). In the basic layout of the measuring site, the probe must be connected to the level meter (usually vector analyzer) by means of appropriate transmission lines, such as coaxial cable or waveguide. And this entails two main disadvantages of these standard methods [4]:

• Metal transmission lines, which are in the vicinity of the measured antenna, greatly distort the field by the local short-circuiting tangential components of electric field. This occurs even when using very thin lines.

• Flexible transmission line does not usually provide adequate stability of amplitude and phase measurements at high frequencies.

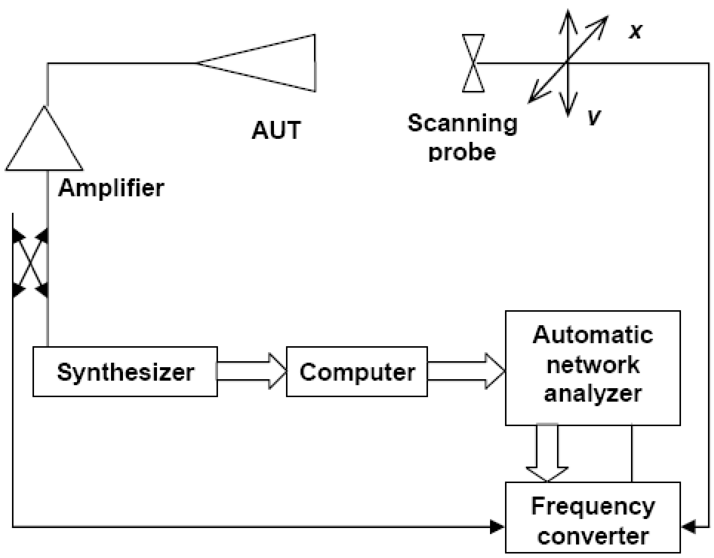

Fig. 2 Setup of the conventional near-field measurements [4]

For these two reasons, the direct measurement (amplitude and phase) method is not suitable for testing the near-field in the vicinity of the antenna at high frequencies.

The NF-FF transformation procedures are based usually on the knowledge of near field complex values. A suitable numerical processing is then applied for the far field reconstruction. Several transformation schemes have been developed for different geometries of the scanning surface, the choice among them being made according to the radiating properties of the AUT and to the required hardware complexity. In fact a trade-off between the mechanical specifications on the scanning system and the numerical processing complexity must be made.

For my doctoral thesis, cylindrical and planar scanning was chosen. Firstly, they are relatively simple and they represent the basic measurement method in the near-field. Secondly, they belong among the most widespread and most appropriate methods for their versatility. Cylindrical scanning is often used for antennas which have a narrow pattern on one axis and a broad pattern on a second axis but can be used also for directional antennas. Planar scanning is suitable for high-gain antennas.

2.2 CONTEMPORARY PHASE RETRIEVAL METHODS

As was already mentioned, high accuracy in the reconstructed pattern requires high accuracy in the measured amplitude and phase of the near field. Such accuracy is much more difficult to achieve for the phase measurement than for the amplitude one. In fact, the probe positioning errors of the scanning system result essentially in uncertainties on the detected phase. Furthermore, the phase measurement is more sensitive to the equipment inaccuracies than the amplitude one. Therefore, it is necessary to use sophisticated measuring devices, which, however, are correspondingly costly. With increasing frequency, the complexity and cost of these devices is increasing significantly. Efforts to avoid the phase measurement lead through phaseless measurements, i.e. to obtain radiation patterns in the far region from only the knowledge of the amplitude distribution in the near region.

Phase retrieval techniques are based on phaseless measurements in the near region. Phase information is then restored using numerical minimize and iterative methods. The idea of the phase reconstruction from only the amplitude is not completely new; it comes from other scientific areas of the electromagnetic theory, especially from optics domain and electron microscopy. In the antennas domain, the idea appeared in the 1980s and the first works interested in near-field measurement based on amplitude only were published by Naples group of scientists at the beginning of the 1990s [8]. They used the method of functional minimization for reconstruction of phases. During the 1990s, the scientists from the University of California (UCLA) started to solve the problem of phase reconstruction too. In contrast to Italian group they use simple Fourier iterative algorithm [13].

At the beginning of the 2000s, local optimization procedure utilizing phaseless electric field data over arbitrary shaped surfaces for the reconstruction of an equivalent magnetic current density which represents the radiating structure or an antenna under test was exploited [16]. In an attempt to make use of the benefits of interferometric and functional methods, a novel hybrid procedure for far-field reconstruction from phaseless near-field data was proposed by a scientist from university of Calabria in 2005 [8]. Basically, interferometric approach was adopted to retrieve the near-field phase from amplitude-only measurements, which were collected by a simple microstrip circuit used in conjunction with two identical probes moving on the scanning surface.

2.2.1 Current minimization methods

Functional minimization method

The functional minimization method is based on the minimization of the difference between the calculated amplitudes and measured ones on two surfaces in the near-field region. The aim is to reveal the minimal function representing the complex intensity of the electric field distribution. If the phase distribution is known, we are able to determine the antenna radiation patterns.

Known minimization algorithms were used to solve the functional. These algorithms can be divided into local and global ones. The local minimization is used when choosing an initial estimate in the area of the global minimum. In contrast, the use of the global algorithm is not conditioned by any choice of the initial estimation, but the convergence can slow down [4].

Appropriate choice of the minimizing method and proper geometric arrangement of scanning planes affect significantly the resulting accuracy of the reconstructed radiation patterns. At present, the functional minimization is mainly based on the local minimization methods (e.g. the Newton method) [8]. Generally, a functional has not only one minimum, but shows, except global minimum, several local minima. The number of local minima increases with increasing error rate of measured amplitudes [12]. To ensure that the minimizing process does not get stuck in a local minimum, several approaches can be used.

- Appropriate choice of the initial estimate of the field distribution which must lie in the area of the global minima (roughly measured phase on one of the scanning plane) [9].
- Modified functional in the form which shows no local minima [10]. Necessary condition for local minima elimination is to use the measured amplitude data which have minimal mutual correlation. This can be achieved by the maximum separation of the scanning planes [10]. This limitation has been overcome by using two scanning probes instead of the two scanning planes [11]. In practical terms, it means replacing two sets of the measured amplitude on the two planes with two sets of the measured amplitude on a single plane, but using two different measuring probes (with different radiation patterns).
- Using global optimization techniques for finding the global minimum. Particle swarm optimization was used for minimizing of the functional [4]. In contrast to the local minimization, the use of the global approach is not conditioned by the choice

of the initial estimate and an additional modification of the minimized functional. On the other hand, minimizing process is not able to reach accurate results and also the convergence is relatively very slow.

Fourier iterative algorithm

Fourier iterative algorithm (FIA) also minimizes the similarly defined functional. Initial estimate is refined in every step and the whole cycle is finished when difference between the current and the previous value is less than the defined value or when the difference between measured and estimated amplitudes is less than required accuracy. Iterative algorithm is simpler and more straightforward compared to the method of functional minimization since it does not need to implement any numerical methods to minimize the functional [13]. On the other hand, convergence can be slower than by using numerical methods.

The success of using Fourier iterative algorithm as well as other local methods depends on the choice of the initial estimation of the electric field on the antenna aperture. If this initial estimation is very rough, the method can get stuck in a local minimum [13]. Recently, the initial estimation was obtained by phase distribution roughly measured on one of the scanning planes [14]. At present, it is the electric field distribution on the antenna aperture obtained by transformation of the amplitude distribution from the first scanning plane and followed by cutting to the size of the antenna aperture which is used for the choice of the initial estimation [4]. The disadvantage is that this estimation can not be used for antennas with significantly non-uniform distribution in the antenna aperture. Further, the global optimization technique, differential evolutionary algorithm (DEA), is used in conjunction with Fourier iterative algorithm [15].

2.3 DISSERTATION AIMS

Currently, the standard measurement of the near field (measuring amplitude and phase) are implemented in commercial products and NF-FF transformations are brought to perfection at all three types of basic scanning surfaces. Further research in this near field measurements could be aimed at the new scanning geometries and the transformations from near to far field but this is practically impossible without the appropriate equipment. Therefore, searching for the new procedures in the conventional near field measurements is not considered fruitful.

2.3.1 Effective minimization of the functional

Phaseless measurements still represent a current and open problem. This is especially true with respect to the effective minimization of functional which is the biggest issue connected with these methods. Currently, additional information about the measured antenna, rough phase measurement on the whole scanning surface or global optimization are used in minimization methods to avoid getting stuck in a local minimum. One of the main aims of this thesis lies in effective minimization of the functional.

Minimization functional methods suffer from large computational efforts, especially in the cases when we have to analyze radiation properties of electrically large antenna. In this case, the problem description comprises several thousands of unknowns, and CPU-time demands of the minimizing process are enormous. Under these circumstances, there is the idea of representation of the unknown electric field distribution by a few coefficients.

In this thesis, the novel method combines global optimization with compression method. The global optimization method (GO) is used for minimizing the functional and compression method (CoM) is used for reducing the number of unknown variables. This algorithm is used for obtaining the initial estimation. To reach global minima with sufficient accuracy, the common Fourier iterative algorithm is subsequently used.

In order to make this algorithm effective, investigation of using amplitude from only one scanning plane for reconstruction of radiation pattern will be discussed. Thus, the process of obtaining retrieved phase is simplified and made faster.

2.3.2 Application of the novel phase retrieval algorithm for cylindrical geometry

From the mathematical point of view, the planar phase retrieval schemes are least difficult. Their implementation is very easy and therefore they are the subject of the most functional based phase retrieval techniques. Since the cylindrical phase retrieval techniques have received considerably less attention, the novel approach will be applied also for cylindrical geometry which is suitable mainly for antennas having a narrow pattern on one axis and a broad pattern on a second axis.

3 EFFECTIVE MINIMIZATION OF FUNCTIONAL

Both these functional approaches have some disadvantages. Fourier iterative algorithm is conditioned by the choice of the initial estimate lying in the area of the global minimum. On the other hand, global optimizations allow the choice of a random initial estimate but minimizing process is not able to reach precise results and also the convergence is relatively slow. However, there is the possibility to combine the global optimization and the Fourier iterative algorithm [7]. First, the minimization algorithm is used to find an initial estimate lying in the area of the global minimum. The second part consists of the common Fourier iterative algorithm improving the initial estimate. We will pay particular attention to the minimization method.

Under these circumstances, the properties of minimization algorithm are investigated. Selection of the minimization approach, the optimization technique and the appropriate functional influence mainly properties of the algorithm. To reveal the global minimum area faster, the possibilities of accelerating minimization algorithm are also considered. An algorithm of such design works very effectively in case of electrically small antennas.

Problem description comprises several thousands of unknowns, and CPU-time demands of the minimizing process are enormous especially when we have to analyze radiation properties of electrically large antennas. Under these circumstances, the unknown electric field distribution can be represented by a few coefficients. A novel method combining global optimization with a compression method is presented in a different part of this thesis.

Other investigations are focused on the possibilities of using amplitude from only one scanning plane for reconstruction of radiation pattern.

3.1 NOVEL PHASE RETRIEVAL ALGORITHM

The novel method combining global optimization with compression method is also based on amplitude measurements in two different distances from AUT. The GO is used for minimizing the fitness function (functional) and the CoM is used for reducing the number of unknown variables [20], [20].

To reveal of the global minimum faster, different analyses of the minimization method properties were performed. The choice of the minimization approach, the optimization method, the CoM and the choice of the functional were investigated because they influence mainly the properties of the novel algorithm. On the base of these analyses, the minimization algorithm is designed [20], [21], [24].

3.1.1 GO/CoM/FIA method

The goal of the algorithm is to reveal the minimal function representing the complex intensity of the electric field distribution on the aperture of the measured antenna. If the phase distribution on the aperture is known, both, phase distribution on both scanning planes and the antenna radiation patterns can be determined. The algorithm assumes knowledge of amplitude sets on two scanning planes, scanning planes distances from the AUT and dimensions of the AUT (shown in Fig. 3).

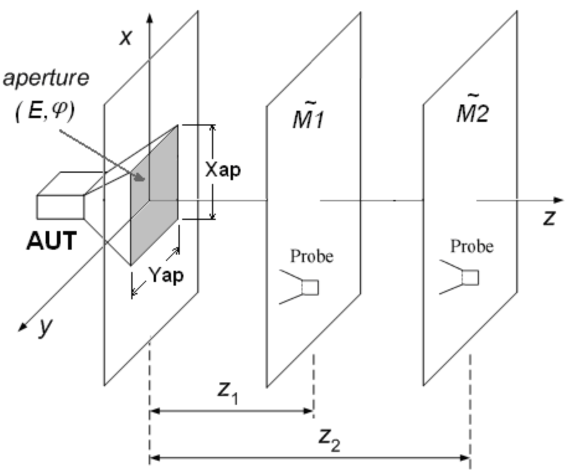

Fig. 3 Principle of the GO/CoM/FIA method

On the basis of the previous analysis, the minimization algorithm was designed. Unlike [4], the new minimizing approach is exploited in functional based method.

This approach based on the principle of the FIA shows much better convergence properties. Due to exploitation of the GO, the algorithm is not conditioned by any choice of the initial estimate lying in the area of the global minimum but the convergence can slow down. From this point of view, two optimization techniques were chosen, Real-Coded Genetic algorithm and Particle Swarm optimization. Which method will be used depends on the number of optimized variables.

Two image compression methods were considered for reducing the number of unknown variables and due to better compression properties the discrete cosine transform (DCT) is chosen for reconstruction of the radiation patterns [18].

The choice of the minimizing functional is also very important. According to the analysis the fitness function was selected and has the following form [21]:

$$F = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\left|E_1(i,j)\right|^2 - \widetilde{M}_1(i,j)^2\right]^2 \cdot \widetilde{M}_1(i,j) + \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\left|E_2(i,j)\right|^2 - \widetilde{M}_2(i,j)^2\right]^2 \cdot \widetilde{M}_2(i,j) \qquad (1)$$

In formulas, $E_1(i, j)$ and $E_2(i, j)$ are the computed complex electric field values in the point i, j on the first scanning surface and the second one, respectively. $\widetilde{M}_1(i,j)$ and $\widetilde{M}_2(i,j)$ are the measured amplitudes in the point i, j on the first scanning surface and the second one, respectively.

The flow chart of the minimization algorithm exploiting GO and CoM is depicted in Fig. 4. First, random initial guess of the DCT coefficients is made. After the inverse DCT is carried out, we obtain electric field distribution on the antenna aperture. Zero padding is applied to the distribution to get the same extension as the scanning surfaces have. After this operation, the initial electric field on aperture is transformed (using FFT) to the plane wave spectrum (PWS) and moved by the propagation constant to the distance of the first scanning plane. In the next step, the calculated amplitudes of the first plane are replaced with the measured ones. The resultant field is then propagated to the next plane, and the calculated amplitudes of the second plane are again replaced with the measured ones. Field in second plane is projected back to first plane and the error function is calculated according the same fitness function (1) but only for first plane.

We have to take into account that the lossy compression method is used so the accuracy of retrieved far-field may not be sufficient in some cases. Then the accuracy of the retrieval scheme can be improved by a local method. So, in the next phase, the FIA which minimizes the same functional is chosen to improve the initial estimate obtained by minimization method. Flowchart of the FIA is depicted in Fig. 17.

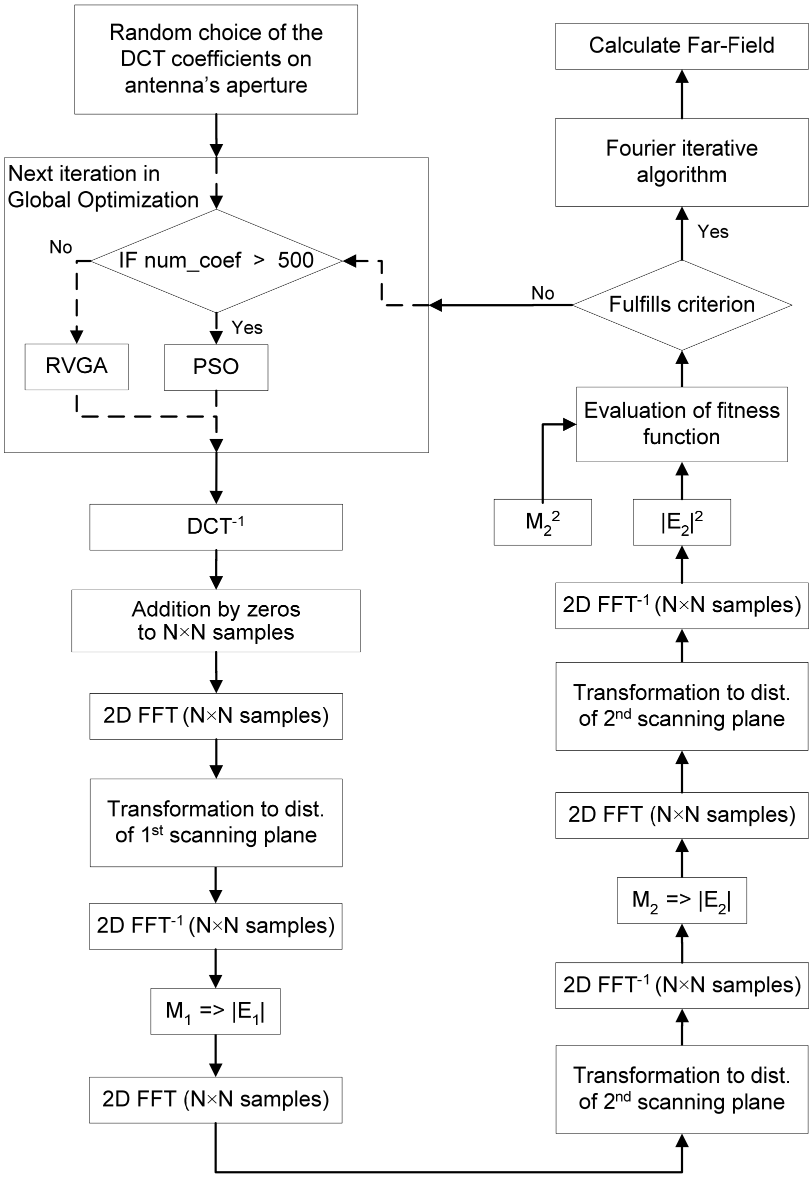

Fig. 4 Flow chart of the minimization algorithm exploiting the global optimization and the compression method

3.1.2 Comparison of novel minimization algorithm with others

Most current algorithms use the local methods to minimize of the functional purely [8] - [11], eventually a simple iteration [13], [14]. But, they require appropriate choice of the initial estimate, or they have certain restrictions on the minimum distance between scanning planes, etc. The use of global optimization techniques to find the initial estimate is relatively new and it brings considerable simplification and acceleration of the whole minimization [4], [15]. Their implementation is very simple and takes only a few lines of the source code. Moreover, because the field distribution on the antenna aperture is minimized (not the field on some of the scanning planes), the minimization is computationally inexpensive and faster. At the same time, the use of GO reduces the number of the

Fourier transformations performed to a half compared with the algorithm presented in [9]. This speeds up the whole minimization significantly again.

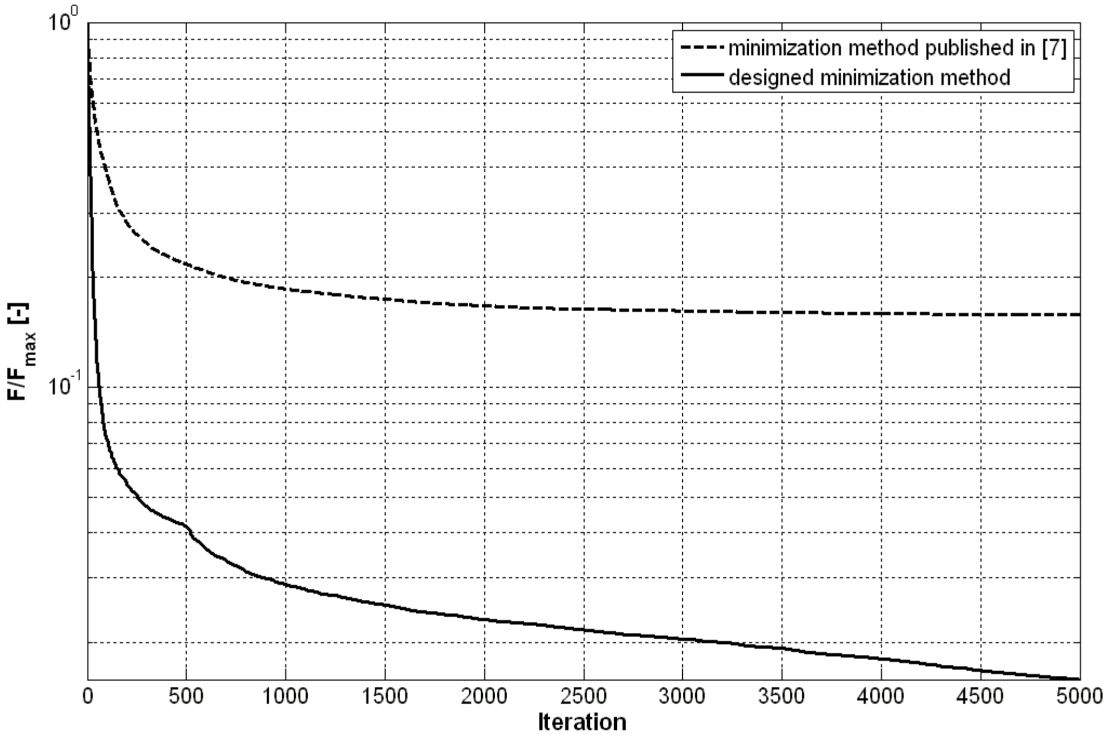

Fig. 5 Comparison of the till now published algorithm and designed one

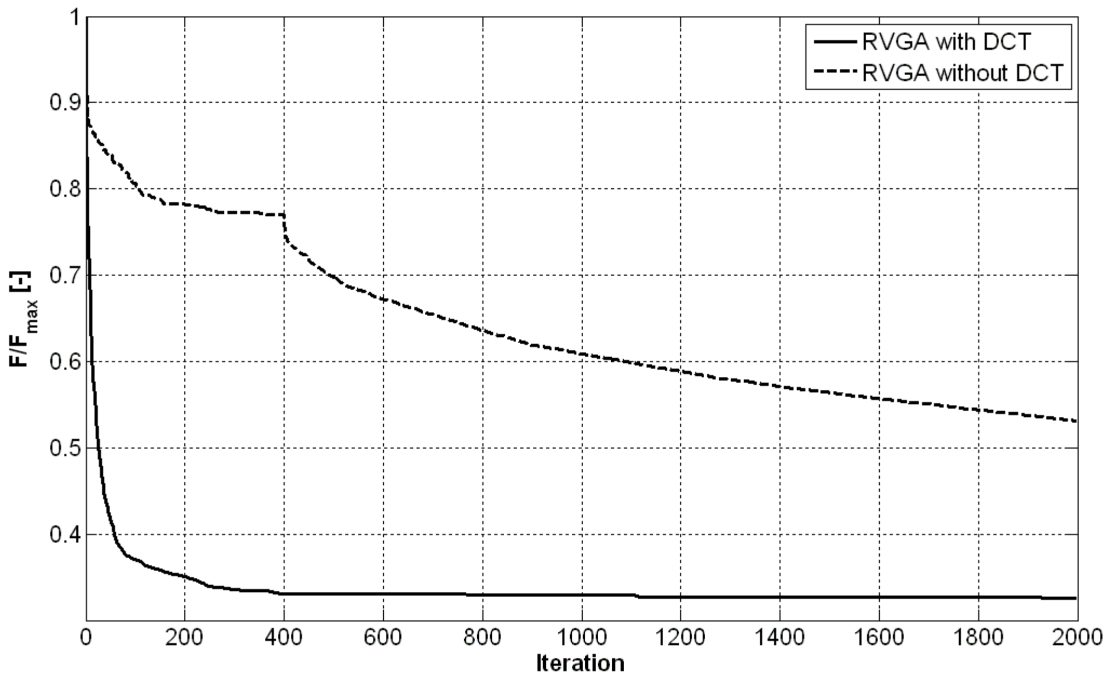

Fig. 6 Comparison of convergence properties for algorithms without DCT and with DCT

Fig. 5 compares the published minimization method exploiting PSO [4] with the designed one. Comparison is carried out for data of the horn antenna, so only 390 unknown were optimized. In this case RVGA was used and it is obvious that much better convergence behavior compared with minimization algorithm in [7] can be obtained by suitable choice of minimization algorithm parameters.

In Fig. 6, we can see the comparison of convergence properties for minimization algorithm without the DCT and with the DCT. The convergence properties were investigated for the antenna with 7 442 unknowns. As it is obvious, the algorithm using the DCT exhibits better convergence properties. Although the implementation of the compression method is a quite time-consuming operation, the algorithm brings remarkable optimization time savings. The algorithm with the DCT is approximately eight times faster than without it. It is because only a fraction of the coefficients representing searched electric field on antenna aperture is optimized.

3.1.3 Application of GO/CoM/FIA method for radiation pattern reconstructions

The verification of the described novel method was carried out on the radiation pattern reconstruction of the antenna array and the lens antenna. The antenna array (13×27 elements) is analyzed at 10 GHz and has 1 271 complex unknowns.

The measurements of the lens antenna for the analysis were carried out at Aalto University School of Science and Technology, Finland (formerly TKK Helsinki University of Technology). The lens antenna and the measurement setup are briefly described in [8]. The lens antenna with the reflector diameter of 60 mm was analyzed at frequency 310 GHz and has 18 225 complex unknowns.

The antenna array

In the case of the antenna array the algorithm without DCT was used. The possibility of using initial estimate (consisting of amplitude obtained from the first scanning plane and uniform phase distribution) and the combination of different functionals was investigated for accelerating the radiation pattern reconstructions.

The far-field results obtained after using the novel method are shown in Fig. 7 and Fig. 8. The reconstructed radiation patterns are in a good agreement with the pattern obtained by the direct transformation of the complex near field.

To conclude, it was found out that if we reconstruct the radiation pattern of antenna having relatively simple electric field distribution on antenna aperture and the radiation pattern perpendicular to the scanning plane, we can use initial estimate obtained from the first scanning plane as estimate lying in the area of the global minimum. If the antenna has more complex electric field distribution on antenna aperture, the application of the designed minimization method is preferable.

It was also found out that the designed algorithm using combination of functionals and exhibits faster convergence rate and more precise reconstructions than in the case where only the functional is used but the accuracy obtained by minimizing algorithm is not sufficient in most cases. So if the precise knowledge of the antenna radiation patterns is required, it is necessary to use the local minimization method (FIA) for their refinement [21].

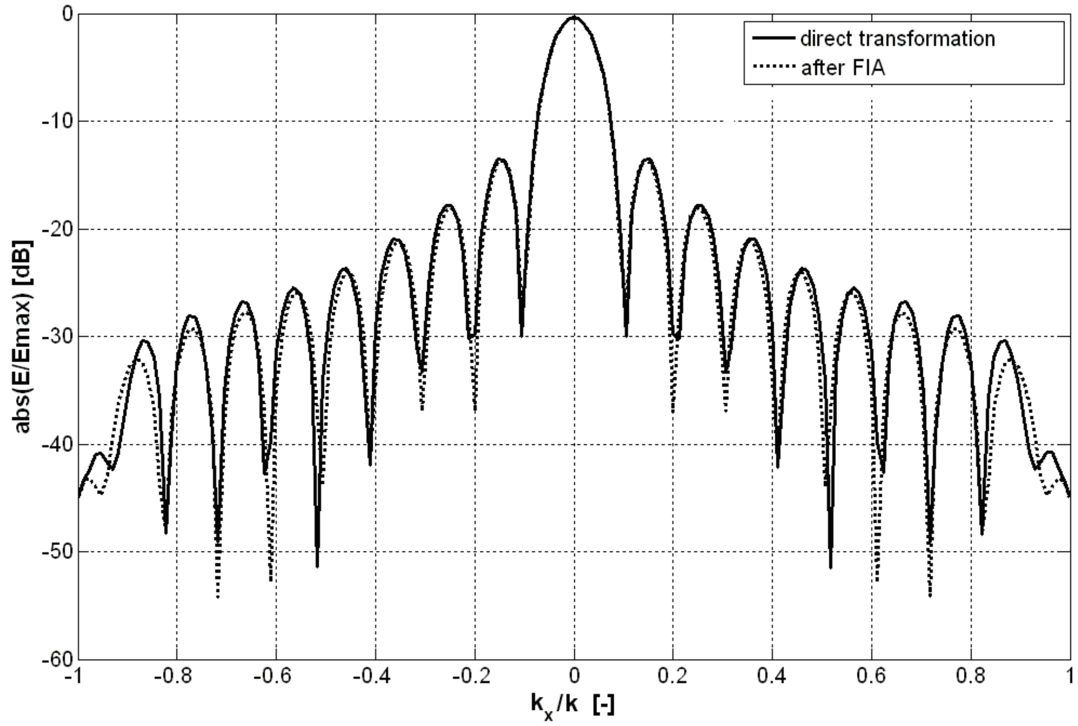

Fig. 7 Reconstructed H plane radiation pattern of the antenna array after applying method

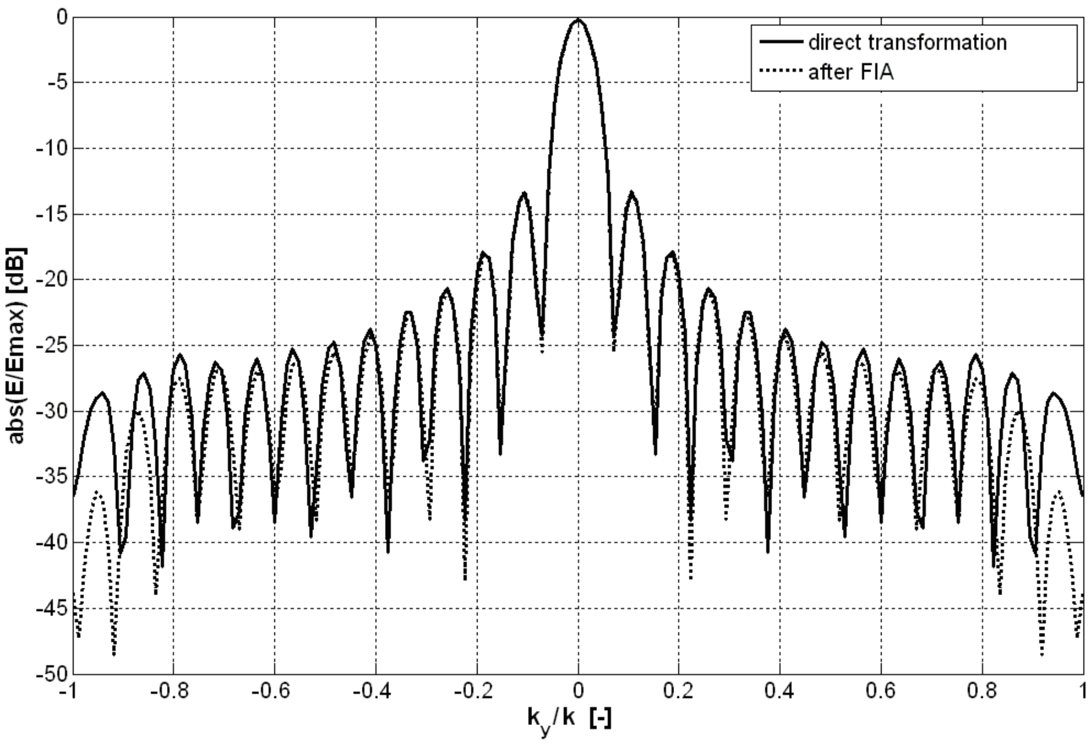

Fig. 8 Reconstructed E plane radiation pattern of the antenna array after applying method

The first part of the designed algorithm uses global optimization to find the initial estimate, which lies in the area of global minimum. The use of GO to minimize the functional brings a significant simplification and acceleration of the whole minimization. The implementation of the global optimization is very simple and takes only a few lines of source code. Since the minimized field distribution on the antenna aperture is always smaller than the electric field distribution on the scanning plane, the algorithm is faster and computationally less expensive. The second part of the minimizing algorithm is the FIA which improves the initial estimate obtained by the GO. The attainable accuracy of the obtained radiation patterns after applying the designed algorithm with FIA is comparable with other published methods, especially with methods based on local minimization of functional [4], [8] - [11] and [13].

An algorithm designed in this way works very effectively for electrically small antennas. But especially when we have to analyze radiation properties of electrically large antennas, the problem description comprises several thousands of unknowns, and CPU-time demands of the minimizing process are enormous. Using image compression method is necessary.

The Teflon lens antenna

In case of the lens antenna the solution space contains 18 225 complex parameters which optimal values should be found out and only approximately 900 coefficients (5 % of all the coefficients) were used for the initial reconstruction of the phases and amplitudes on the antenna aperture by PSO/DCT method. The far-field results obtained after applying the designed method are shown in Fig. 9 and Fig. 10. The agreement between the far-field obtained from the retrieved and directly measured near-field amplitude and phase is excellent in domain k_x/k (k_y/k) = ±0.4.

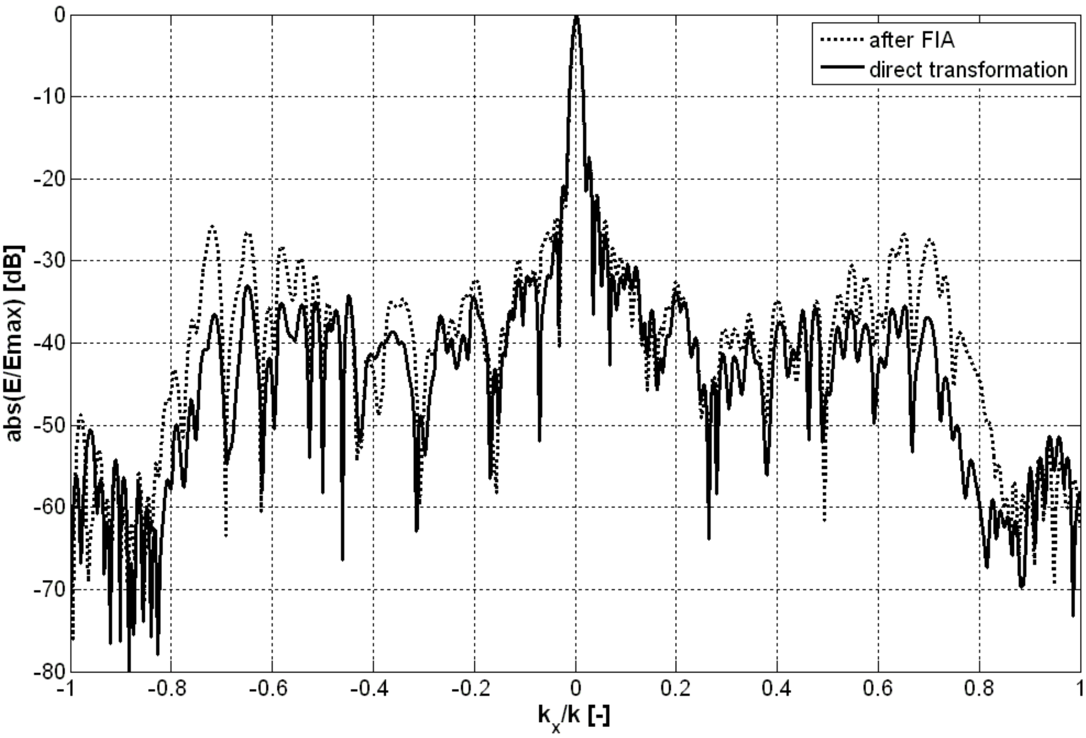

Fig. 9 Reconstructed H plane radiation pattern of the lens antenna and comparison with radiation pattern obtained from measured complex near field

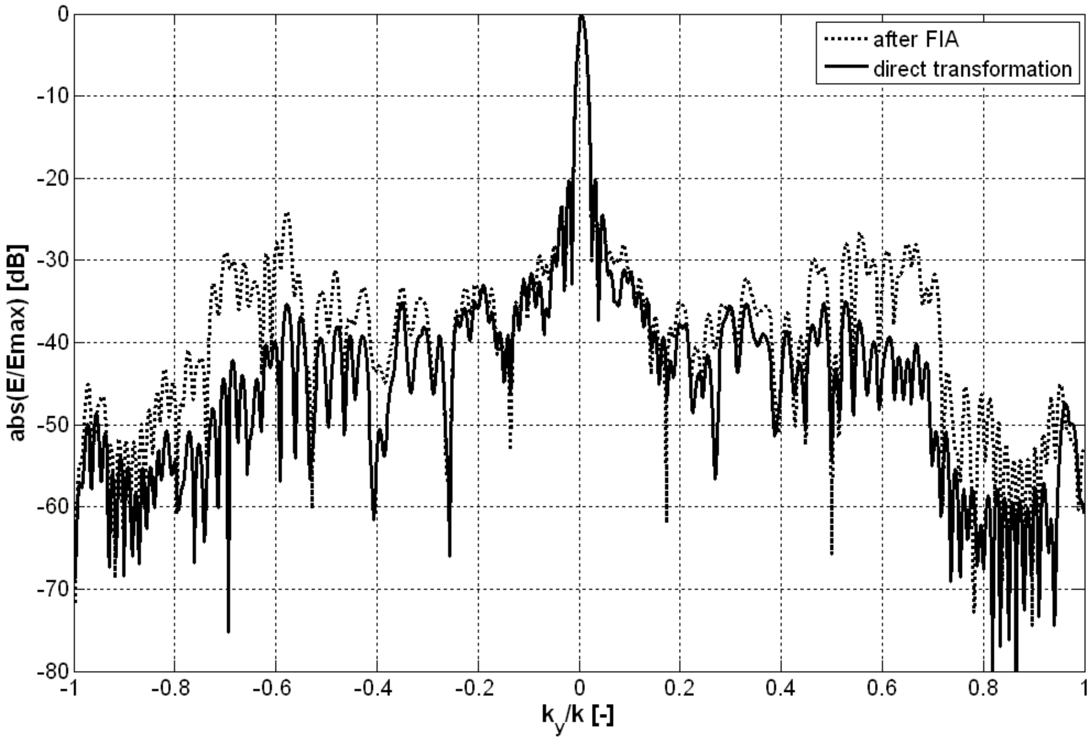

Fig. 10 Reconstructed E plane radiation pattern of the lens antenna and comparison with radiation pattern obtained from measured complex near field

To conclude the novel near-field phaseless approach for the antenna far-field characterization was presented in this chapter. The method combines the global optimization, the compression method and the Fourier iterative algorithm in conjunction with conventional two-plane amplitude measurements. The GO is used to minimize the functional, the CoM is used to reduce the number of unknown variables, and the FIA is used to improve the estimate achieved by GO/CoM.

The proposed algorithm is very robust and faster than minimization algorithms published so far. The algorithm does not require any initial guess in the region of the global minima or any additional information about the AUT. Initial estimate is obtained very quickly in a few tens of iterations. The described algorithm was applied for the phase reconstruction of two electrically large antennas (dish antenna and lens antenna). The accuracy of the far-field patterns obtained by the phase retrieval algorithm is comparable with other minimization methods.

3.2 POSSIBILITY OF SINGLE AMPLITUDE MEASUREMENTS

The classic minimization methods are based on the minimization of the difference between the calculated amplitudes and the measured ones on two plane surfaces (on a single surface with two different probes) in the near-field region. In this section of the thesis, the possibility of using amplitudes from only one scanning plane in functional based method is discussed and compared with two-plane algorithm [24].

3.2.1 Single-plane functional based algorithms

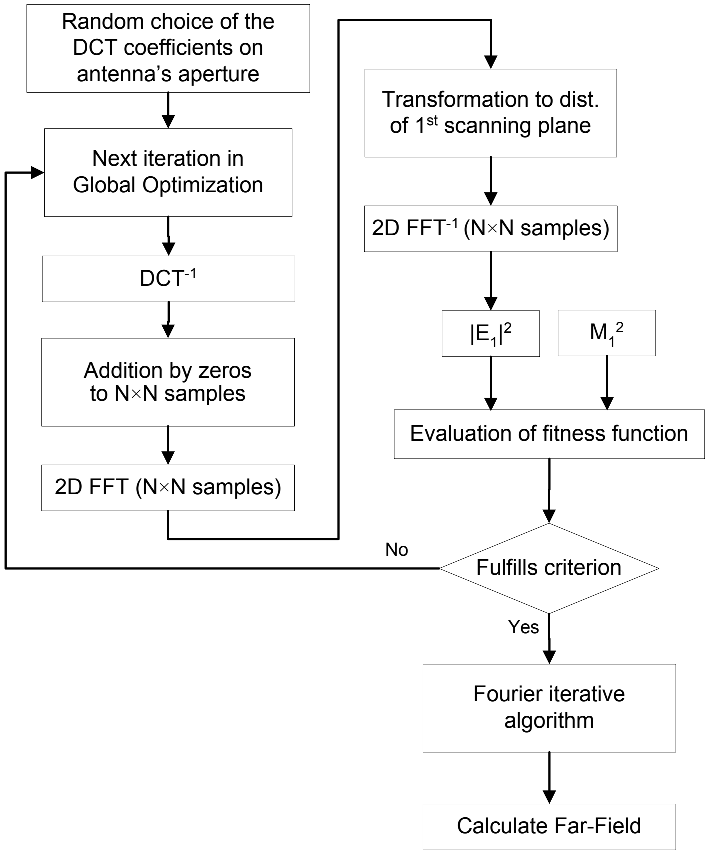

Fig. 11 Flow chart of the single plane minimization algorithm

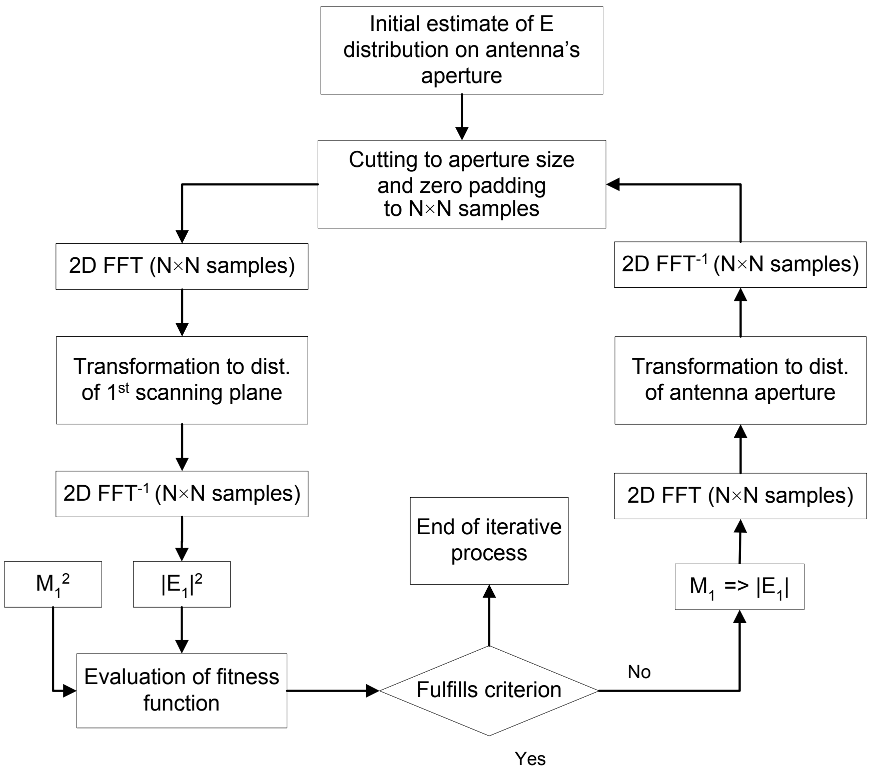

Fig. 12 Single plane Fourier iterative algorithm

The principle of this method is the same as of the previous ones and exploits combination of the global technique with local one. Since only one set of the measured amplitudes is used, the minimization process is simplified and speeds up compared with the two-plane algorithm. The single-plane algorithm of the functional minimization assumes knowledge of the amplitudes on one plane, scanning plane distance from the AUT and dimensions of the AUT. The flow chart of the algorithms is the same like two-plane algorithm but only one branch is used, see Fig. 11 and Fig. 12.

3.2.2 Comparison of the single-plane and two-plane algorithms

The comparison of the single-plane and two-plane algorithms was done on data of the antenna array and phased antenna array.

The single-plane minimization algorithm exploiting the GO and the CoM (Fig. 11) was used for initial reconstruction of the phases and amplitudes on the antenna aperture. The estimate was obtained after 20 iterations of the minimization method. The agreement between the retrieved far-fields and the theoretical one was excellent in domain $|k_{x(y)}/k| = 0.2$ (main lobe and side lobes), see blue dotted line in Fig. 13. Fig. 13 also shows improved radiation patterns achieved after using single/two planes FIA. The reconstructed far-field of the antenna array show that the FIA based on one plane amplitudes has achieved comparable results with FIA based on two plane amplitudes.

Far-field reconstruction of the phased antenna array was also made for verification of these considerations. This phased antenna array has the same physical parameters as the previous antenna array but there is difference in the feeding of individual elements. They are fed so that the phase is changed linearly along the axis x and y, resulting phase change in the axis was equal to 65.3°. This resulted in a deflection of the main lobe in the direction $\theta = 14°$ and $\phi = 14$ °.

Initial estimate was obtained by RCGA/DCT method after 20 iterations, dotted blue line in Fig. 14. At first sight it may seem that the initial estimate does not lie in the global minimum but the reconstructed far-field obtained after applying two-plane iterative algorithm proves the opposite, see Fig. 14. We can observe good agreement with theoretical radiation pattern in this case. On the other hand, the single plane FIA is not able to achieved results with required accuracy.

To conclude, it was found out that knowledge of the amplitudes on one plane is sufficient for getting of the initial estimate which lies in the global minimum area. Thus, the process of obtaining the initial estimate can be simplified and speeded up compared with the two-plane algorithm. These considerations were also confirmed for the phased antenna array. The single-plane FIA can be used only if the main lobe is perpendicular to the plane of the antenna and if we reconstruct the radiation patterns of the antenna having relatively simple electric field distribution on antenna aperture then accuracy of the obtained results is sufficient. Otherwise, the accuracy can strongly depend on the problem [24].

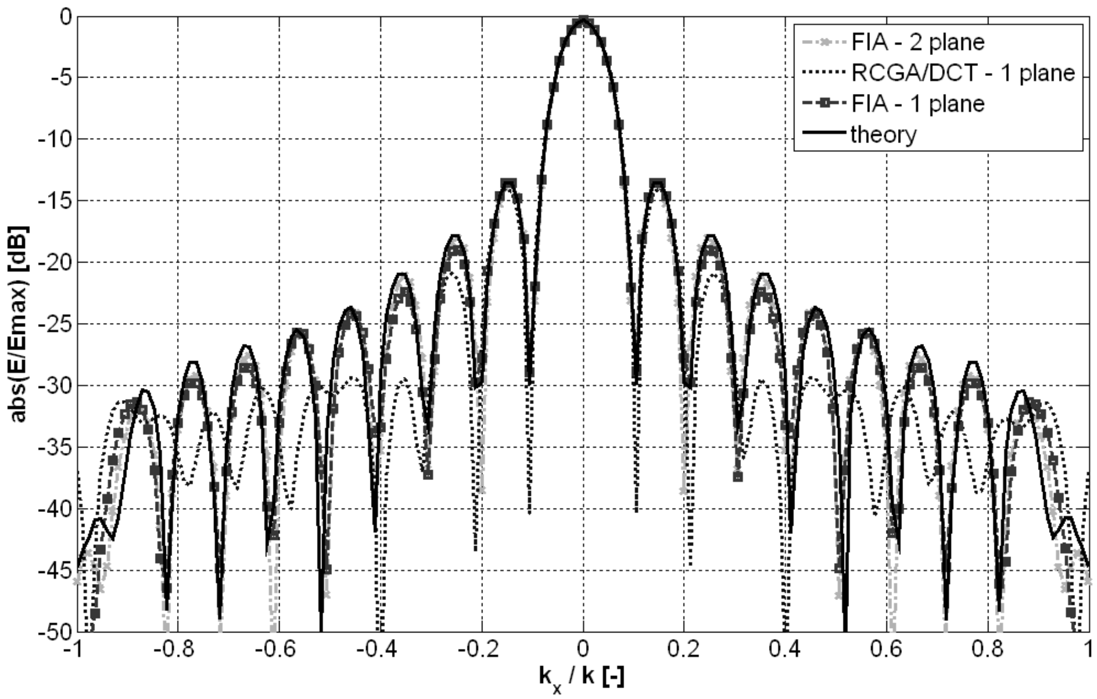

Fig. 13 Reconstructed radiation patterns of the antenna array; H plane

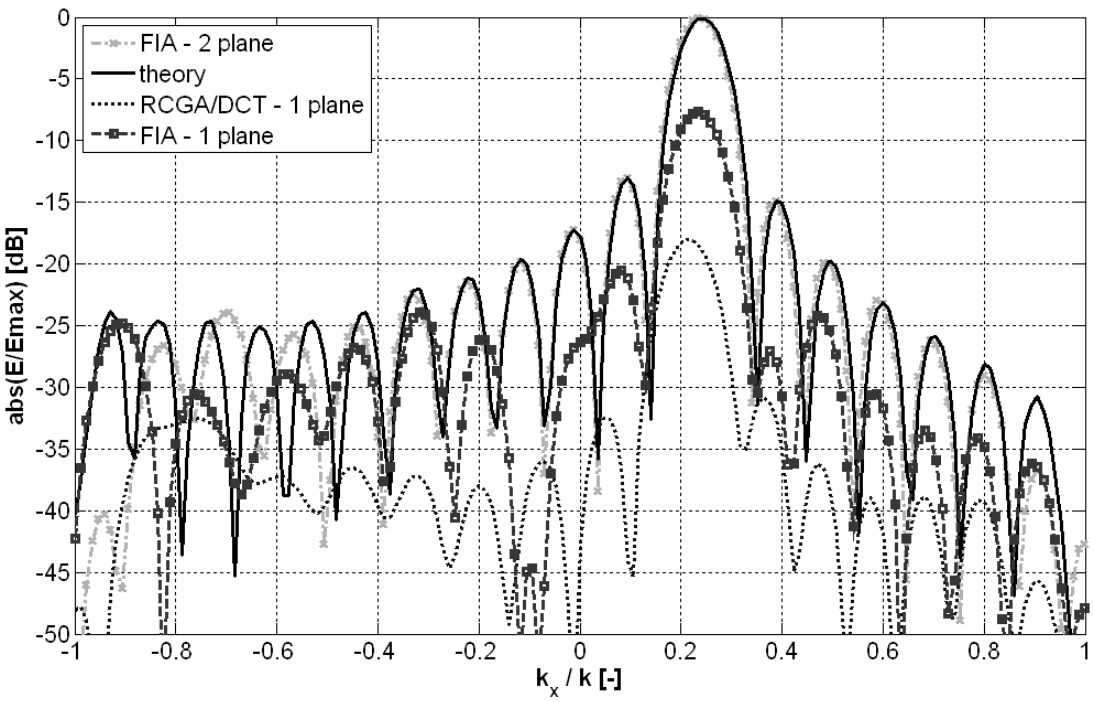

Fig. 14 Reconstructed radiation patterns of the phased antenna array; H plane

4 APPLICATION OF THE NOVEL ALGORITHM FOR CYLINDRICAL GEOMETRY

Planar NF/FF schemes have been the subject of the research in the previous part of the work. In this section, attention will paid to the application of the novel phase retrieval techniques for cylindrical geometry. The cylindrical measurements are more time-consuming than the planar one and from the mathematical point of view the cylindrical phase retrieval schemes are also more complicated for implementation.

4.1 NEAR-FIELD CYLINDRICAL SCANNING

Knowledge of the tangential components on an arbitrary surface, which, ideally, completely surrounds the measured antenna, allows calculating the field anywhere outside this surface, including in far region [4], [5]. However, the practical implementation of cylindrical scanning requires the scanning cylinder of final dimensions. Using the scanning cylinder of final dimensions carries an error in the calculated far field. The size of this error is dependent on the relative intensity of the field outside the scanning cylinder (i.e. on the size of the field, which is failure due to final scanning cylinder) [3].

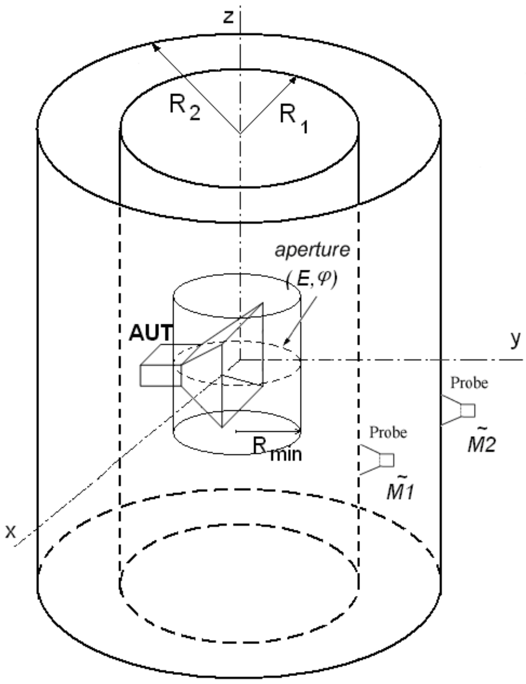

Fig. 15 Relevant to scanning geometry

Cylindrical near-field scanning can provide complete angular coverage of the AUT field in horizontal plane but it is limited by the finite height of the cylinder in the vertical plane. The minimum radius of the scan cylinder enclosing AUT must be greater than $R_{\min}$, where $R_{\min}$ is the largest transverse dimension of the AUT in given cut. Thus, scanning of the antenna near-field is carried out in the interval of the distances $R_{\min}$ and $2D^2/\lambda$.

4.2 PHASE RETRIEVAL CYLINDRICAL ALGORITHM

The designed functional based method was made-over for cylindrical scanning geometry. Unlike in the planar field the goal of the algorithm is to find the minimal value of functional representing the electric field distribution on the cylinder with minimum radius R_{min}, see Fig. 15. The radius $R_{\min}$ corresponds to the largest transverse dimension of the AUT [26]. Also in this case of the cylindrical scanning the amplitudes on single and two cylinder surfaces will be assumed and comparison of the methods will be done.

Since it was found out that the backward transformation is less accurate than the forward transformation the classic minimization approach instead of the new one is used [22]. The classic minimization approach does not employ backward transformation. Otherwise the cylindrical minimization algorithm was designed according to the planar algorithm. The fitness function to be minimized has also the same form (1).

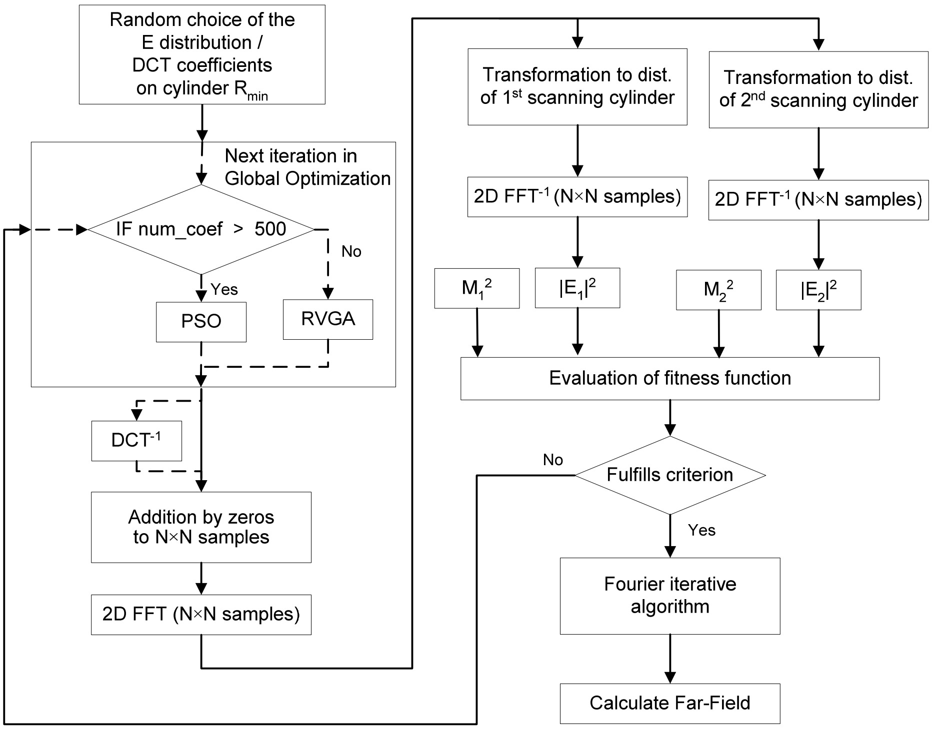

Fig. 16 Flow chart of the cylindrical minimizing algorithm

The classic approach used in the designed minimization method is shown in Fig. 16. First, random initial estimate of the electric field distribution on the cylinder R_{min} is performed. Zero padding is applied to the distribution to get the same extension as the scanning surfaces have. After this operation, the initial electric field is propagated using Hankel functions to the distance of the first and the second scanning surfaces. In the next step, the computed and the measured amplitudes are compared. For electrically large antennas the minimization algorithm is complemented by the image compression method (DCT). The procedure is repeated until the maximum number of iterations is reached. In the next part the FIA is used for improving of the initial estimate obtained by minimization algorithm. The made-over algorithm for cylindrical case is depicted in Fig. 17. In the FIA backward transformations are used so we have to keep in mind that we introduce error into the algorithm by using backward transformations. Finally, the calculated electric field distribution on cylinder R_{min} is used to calculate the far-field pattern of the antenna. [27].

In the case of the single-plane algorithms the schemes have only one difference. Since amplitudes on a single surface only are assumed, the transformations to the second cylinder are eliminated.

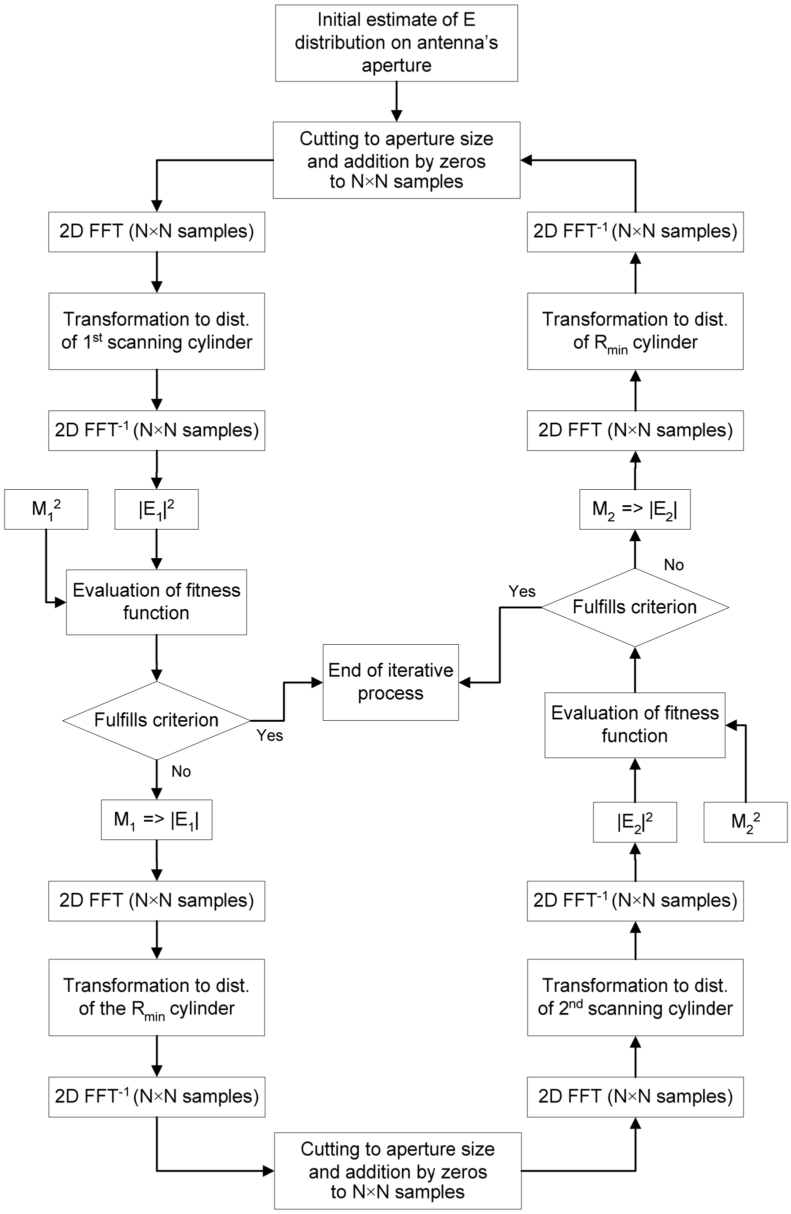

Fig. 17 Flow chart of the Fourier iterative method for cylindrical case

4.3 APPLICATION OF THE DESIGNED MINIMIZATION METHOD FOR RECONSTRUCTION OF RADIATION PATTERNS

The algorithm was also experimentally tested on a standard X-band dish antenna having a reflector diameter of 0.34 m. The experimental measurements were carried out in collaboration with the Microwave Laboratory of the University of Calabria, Italy [17].

The reconstruction was carried out for electric field component E_z only. The minimization approach with the DCT was used for the initial reconstruction of the phases and amplitudes on the cylinder of radius 0.35 m (R_{min}). RVGA/DCT method exploits for the reconstruction 20 coefficients instead of 529 complex parameters representing electric field distribution on cylinder R_{min}. Accuracy of the radiation patterns obtained after one hundred iterations was not sufficient, especially in H plane. It is due to the lossy compression method used. Subsequently, the FIA was used to improve the initial estimate obtained by RVGA/DCT, see Fig. 18 and Fig. 19. For the two-surface FIA, the agreement between the retrieved far-field and far-field obtained by transformation of the complex near-field data is excellent in the domain of the main lobe. We can observe that the retrieved far-field becomes less accurate approximately below -30 dB.

The use of single cylinder FIA showed the problem with reconstruction of radiation pattern, especially in H plane where it was not even able to reconstruct the main lobe. So, knowledge of the amplitudes on one cylinder is sufficient for getting the initial estimate lying in the global minimum. Thus, the process of obtaining the initial estimate can be simplified and speeds up compared with the two-cylinder algorithm. But to refine the results, the two-cylinder FIA is necessary.

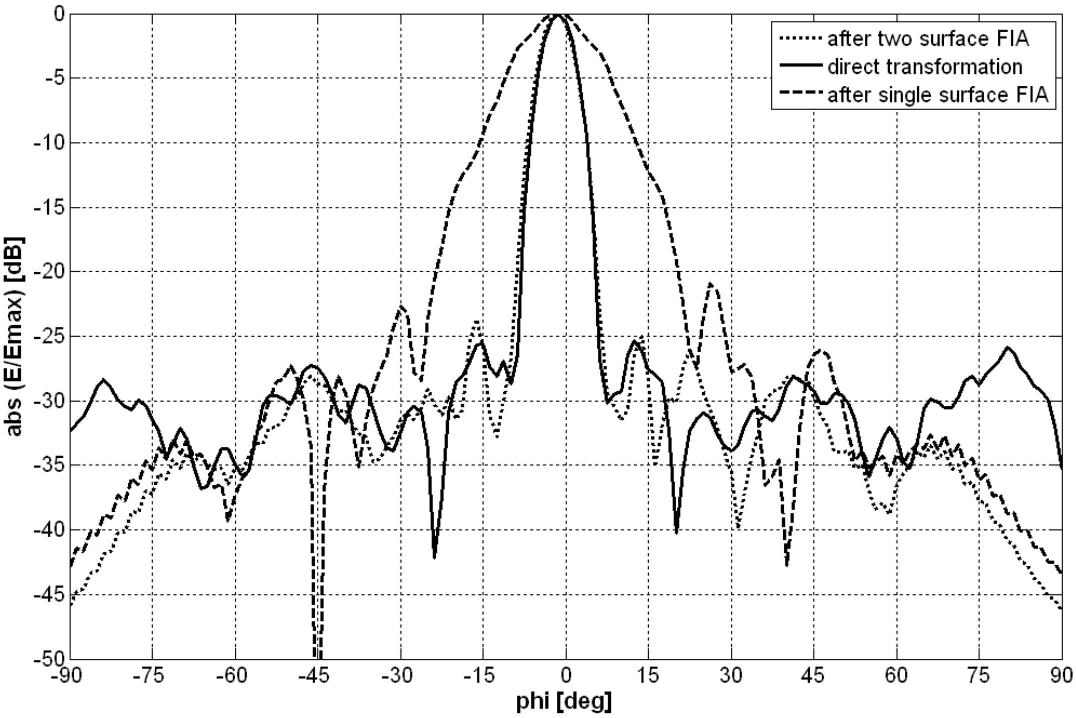

Fig. 18 Reconstructed H plane radiation patterns of the dish antenna after applying the single-surface FIA and the two-surface FIA

The novel phase retrieval method combining global optimization with image compression method and simple iterative method was described in this chapter. The method was applied for the cylindrical near-field phaseless measurements. The designed method eliminates the disadvantages of the previous cylindrical methods [6], [8]. The algorithm does not require an initial estimate in the area of the global minima obtained by a rough phase measurement, and does not need additional information about the measured antenna.

The reconstructions carried out on cylindrical surface confirmed the findings established during the reconstruction on plane surface.

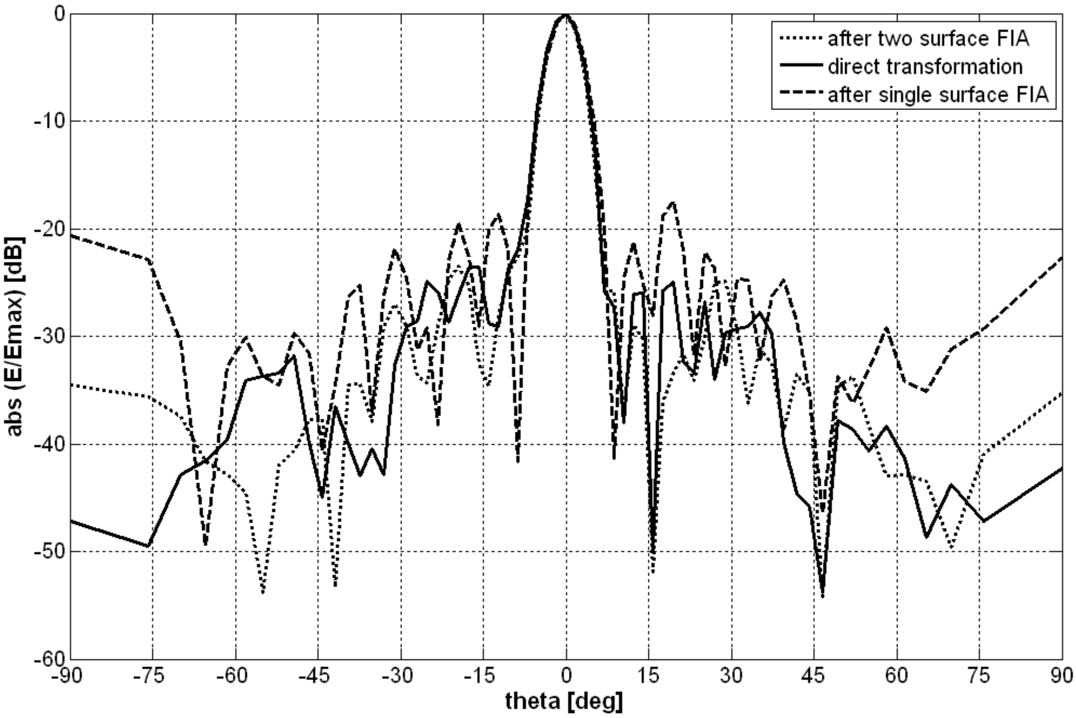

Fig. 19 Reconstructed E plane radiation patterns of the dish antenna after applying the single-surface FIA and the two-surface FIA

5 CONCLUSIONS

This thesis deals with the reconstruction of the radiation patterns from phaseless measurements in the near field. This theme is still current and a complete solution has not been found for many problems yet. Particularly, the effective minimization of the functional and the effective reconstruction of the phase distribution are the biggest problems of all the current methods.

Under these circumstances, the properties of minimization algorithm were researched. The selection of the minimization approach, the optimization technique and the appropriate functional influences mainly convergence properties of the algorithm. That is why they were investigated and appropriately chosen. To reveal the global minimum area faster, the possibilities in the form of initial estimates for accelerating minimization algorithm were also considered. And finally, the idea of representation of the unknown electric field distribution by a few coefficients was implemented into the minimization algorithm.

The novel near-field phaseless approach for the antenna far-field characterization combines a global optimization, an image compression method and a local optimization in conjunction with conventional two-surface amplitude measurements.

The global optimization method is used to minimize the functional, the image compression method is used to reduce the number of unknown variables, and the local optimization method is used to improve the estimate achieved by the previous method. As the minimization tool, two optimization techniques were chosen, Real-Coded Genetic Algorithm and Particle Swarm Optimization. The decision on which method will be used is based on the number of optimized variables. Due to its best compression properties, the Discrete Cosine Transform is considered to reduce the number of unknown variables. The usage of a compression method for reconstruction of phase is completely original and had never been published before this thesis. The Fourier iterative algorithm which is commonly used in the reconstruction of radiation patterns is exploited as a local method.

Other investigations presented in this thesis were focused on the possibilities of using amplitude from only a single scanning surface for reconstruction of the radiation pattern. It was found out that knowledge of the amplitudes on a single surface in the minimization algorithm is sufficient for obtaining initial estimate lying in the global minimum area. Thus, the process of obtaining the estimate can be simplified and speeds up compared with the two-surface algorithm. In the second part of the algorithm, in Fourier iterative algorithm, amplitudes from a single surface can be used only if the reconstruction is performed for antennas having relatively simple electric field distribution on antenna aperture and the main lobe perpendicular to the scanning surface. In these cases, the accuracy of the obtained results is comparable with algorithm using amplitude measurements over two surfaces. Otherwise, the accuracy can strongly depend on the investigated antenna.

The novel phase retrieval algorithm was applied also for cylindrical geometry. The reconstructions carried out on a cylindrical surface confirmed the findings established during the reconstruction on a plane surface.

BIBLIOGRAPHY

[1] SLATER, D. *Near-Field Antenna Measurements*. Boston: Artech House, 1991, ISBN 0-89006-361-3.

[2] YAGHJIAN, A. Z. An Overview of Near-Field Antenna Measurements. *IEEE Transaction on Antennas and Propagation*. 1986, vol. 34, no. 1, p. 30 – 45.

[3] APPEL-HANSEN, J. *“Antenna measurements” in The Handbook of Antenna Design*, vol. 1, London: Peregrinus, ch. 8. 1982. ISBN 0906048826

[4] LEACH, Jr., W. M., PARIS, D. T. Probe-Compensated Near-field Measurements on Cylinder. *IEEE Transaction on Antennas and Propagation*. 1973, vol. 21, no. 7, p. 435 – 445.

[5] YAGHJIAN, A. D. *Near-Field Antenna Measurements on a Cylindrical Surface: a Source Scattering-Matrix Formulation*. Boulder, CO: National Bureau of Standards, 1977, NBS Technical Note 696 (revised).

[6] ISERNIA, T. LEONE, and G. PIERRI, R. A new approach to antenna testing from near field phaseless data: the cylindrical scanning. *IEEE Proc. H*, 1992, 139, pp. 363-368

[7] TKADLEC, R. *Near-Field Antenna Measurements*. Dissertation Thesis. Brno: Brno University of Technology, 2005.

[8] BUCCI, O. M., D’ELIA, G., LEONE, G., PIERRI, R. Far-field Pattern Determination from the Near-field Amplitude on Two Surfaces. *IEEE Transaction on Antennas and Propagation*. 1990, vol. 38, no. 11, p. 1772 – 1779.

[9] LEONE, G., PIERRI, R., SOLDOVIERI, F. On the Performances of Two Algorithms in Phaseless Antenna Measurements. In *Proceedings of the 10th ICAP*. Edinburgh 1997, p. 1/136 – 1/141.

[10] ISERNIA, T., LEONE, G., PIERRI, R. Radiation Pattern Evaluation from Near-Field Intensities on Planes. *IEEE Transactions on Antennas and Propagation*. 1996, vol. 44, no. 5, p. 701 – 710.

[11] PIERRI, R., D'ELIA, G., SOLDOVIERI, F. A two Probes Scanning Phaseless Near-field Far-field Transformation Technique. *IEEE Transaction on Antennas and Propagation*. 1999, vol. 47, no. 5, p. 792 – 802.

[12] NEWELL, A. C. Error analysis techniques for planar near-field measurements. *IEEE Transactions on Antennas and Propagation*. 1988, vol. 36, no. 6, p. 754 – 768.

[13] YACCARINO, R. G., RAHMAT-SAMII, Y. Phaseless Bi-Polar Planar Near-Field Measurements and Diagnostics of Array Antennas. *IEEE Transactions on Antennas and Propagation*. 1999, vol. 47, no. 3, p. 574 – 583.

[14] RAHMAT-SAMII, Y. YACCARINO, R. G. Microwave antenna imaging, diagnostics, and phaseless reconstruction. *Int. J. Imaging Syst. Technol.*, vol. 8, no. 4, pp. 396–406, 1997.

[15] RAZAVI, S. F., RAHMAT-SAMII, Y. A new look at phaseless planar near-field measurements: limitations, simulations, measurements, and a hybrid solution. *IEEE Antennas and Propagation Magazine*, vol. 49, no. 2, 2007, pp. 170-178

[16] PETRE, P. SARKAR, T. K. Planar near-field to far field transformation using an equivalent magnetic current approach. *IEEE Trans. Antennas Propagat.*, vol. 40, pp. 1348–1356, Nov. 1992.

[17] COSTANZO, S. DI MASSA, G. and MIGLIORE, M. D. A novel hybrid approach for far-field characterization from near-field amplitude-only measurements on arbitrary scanning surfaces. *IEEE transactions on antennas and propagation*, vol. 53, no. 6, pp. 1866-1874, June 2005

[18] AHMED, N., NATARAJAN, T., RAO, K. R. Discrete cosine transform, *IEEE Trans. Computer*, vol. COM-23, no. 1, pp. 90-93, 1974.

[19] VON LERBER, A. VIIKARI, LISENO, V. ALA-LAURINAHO, J. AND RÄISÄNEN, A.V. A Feasibility study of phase retrieval algorithms at sub-millimeter wavelengths. In *Proceedigns of The 27th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, Newport, RI, USA, 2005, p. 79 - 84.

SELECTED PUBLICATIONS

[20] PUSKELY, J. NOVÁČEK, Z. Application of the Global Optimization Approaches To Planar Near-Field Antenna Phaseless Measurements. *Radioengineering*. April 2009, Vol. 18, No. 1, pp. 9 - 17. ISSN 1210-2512.

[21] PUSKELY, J. NOVÁČEK, Z. New Look to Real Valued Genetic Algorithm Used to Reconstruct Radiation Patterns. In *Proceedings of the 15th Conference Radioelektronika 2009*. 2009.

[22] PUSKELY, J. NOVÁČEK, Z. Computing of the EM field from only amplitude measurement on cylindrical surfaces. In *Proceedings Králíky 2009.* Brno, Czech Republic: 2009. s. 221-225. ISBN: 978-80-214-3938- 2.

[23] PUSKELY, J. NOVÁČEK, Z. Reconstruction of Antenna Radiation Pattern at 310 GHz Using Image Compression Methods. In *The proceedings of EuCAP 2010.* Barcelona, Spain: 2010. s. 1-5.

[24] PUSKELY, J. NOVÁČEK, Z. Comparison of Different Approaches for Reconstruction of Radiation Patterns. In *Proceedings of the 14th Conference on Microwave Techniques COMITE 2010.* Brno: 2010. s.199-202. ISBN:978-4244-6351-0.

[25] PUSKELY, J. NOVÁČEK, Z. Exploiting of the Compression Methods for Reconstruction of the Antenna Far-Field Using Only Amplitude Near-Field Measurements. *Radioengineering,* 2010, Vol. 19, No. 2, s. 299-306. ISSN: 1210- 2512. 2010

[26] PUSKELY, J. NOVÁČEK, Z. Reconstructing Radiation Patterns Using Amplitude Measurements on Cylindrical Surfaces. In *Proceedings of the International Conference on Electromagnetics in Advanced Applications ICEAA 2009.* Torino, Italia: 2009. s. 52-56.

[27] PUSKELY, J. NOVÁČEK, Z. Far-Field Reconstruction Based on Compression Method from Cylindrical Near-Field Phaseless Measurements. In *Proceedings of the International Conference on Electromagnetics in Advanced Applications ICEAA 2010. Sydney*, Australia: 2010. will be published

CURRICULUM VITAE

Name: Ing. Jan Puskely
Date of birth: September 7th, 1982
Nationality: Czech republic
Address: Hranická 6, 75124 Přerov
E-mail: xpuske01@stud.feec.vutbr.cz

Education:

Since 2007 Department of Radio Electronics (DREL),
Faculty of Electrical Engineering and Communication (FEEC),
Brno University of Technology (BUT)
Ph.D. Study; Doctoral Thesis: “*Reconstruction of antenna near field*”

2005 – 2007 DREL, FEEC, BUT
M.Sc. Study; Diploma Thesis: “*Broadband antennas for EMC testing*”

2002 – 2005 DREL, FEEC, BUT
B.Sc. Study; Bachelor Thesis: “*Baluns*”

Experiences:

05-06 / 2010 Microwave Laboratory, DEIS, University of Calabria, Italy; aimed to antenna near-field phaseless measurement techniques

04 / 2009 TKK Helsinki University of Technology, Espoo, Finland; aimed to antenna measurements at millimeter and submillimeter wavelengths

2008 – 2010 Chairman of IEEE Student Branch Brno University of Technology

Specialization:

Analysis and design of antennas, modeling and simulation of microwave and RF structures, antenna measurement, EMC, design of radio and microwave links

Languages: English – communication level

ABSTRAKT

Cílem disertační práce je navrhnout efektivně pracující algoritmus, který na základě bezfázového měření v blízkém poli antény bude schopen zrekonstruovat anténní blízké pole resp. vyzařovací diagram ve vzdáleném poli.

Na základě těchto úvah byly zkoumány vlastnosti minimalizačního algoritmu. Zejména byl analyzován a vhodně zvolen minimalizační přistup, optimalizační metoda a v neposlední řadě i optimalizační funkce tzv. funkcionál. Dále pro urychlení celého minimalizačního procesu byly uvažovány prvotní odhady. A na závěr byla do minimalizačního algoritmu zahrnuta myšlenka nahrazující hledané elektrické pole několika koeficienty.

Další výzkum byl zaměřen na možnosti využití měřených amplitud pouze z jednoho měřícího povrchu pro rekonstrukci vyzařovacích charakteristik antén a využití nového algoritmu pro rekonstrukci fáze na válcové geometrii.

ABSTRACT

The aim of this dissertation thesis is to design a very effective algorithm, which is able to reconstruct the antenna near-field and radiation patterns, respectively, from amplitude-only measurements.

Under these circumstances, the properties of minimization algorithm were researched. The selection of the minimization approach, optimization technique and the appropriate functional were investigated and appropriately chosen. To reveal the global minimum area faster, the possibilities in the form of initial estimates for accelerating minimization algorithm were also considered. And finally, the idea to represent the unknown electric field distribution by a few coefficients was implicated into the minimization algorithm.

Other investigations were focused on possibilities of using amplitude from only single scanning surface for reconstruction of radiation patterns and the application of the novel phase retrieval algorithm for cylindrical geometry.

BIBLIOGRAPHIC CITATION

PUSKELY, J. Reconstruction of the antenna near-field. *Disertation thesis short version*. Brno: FEEC BUT in Brno, 2010. 30 p.