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Published in IET Microwaves, Antennas & Propagation
Received on 31st July 2013
Revised on 25th October 2013
Accepted on 16th November 2013
doi: 10.1049/iet-map.2013.0406

ISSN 1751-8725

Cosecant-squared pattern synthesis method for broadband-shaped reflector antennas

Ali Akbar Dastranj[1], *Habibollah Abiri*[1], *Ali Reza Mallahzadeh*[2]

[1]*School of Electrical and Computer Engineering, Shiraz University, Shiraz 7134851154, Iran*
[2]*Faculty of Engineering, Shahed University, Tehran 3319118651, Iran*
E-mail: adastranj@shirazu.ac.ir

Abstract: A new technique based on the invasive weed optimisation (IWO) algorithm and geometrical optics (GO) method for synthesising broadband cosecant-squared pattern reflector antennas is presented. The main feature that distinguishes this technique from others is the wide bandwidth. Moreover, compared with the previous methods, the proposed method allows to obtain extremely smaller ripples in the shaped region and lower sidelobe level (SLL). To achieve the desired performance over the entire 18–40 GHz operational bandwidth, the reflector surface is synthesised using a complex and accurate frequency-dependent fitness function including optimum weighting values. The simulation results via FEKO software package further prove the validity and versatility of this technique for solving reflector synthesis problems. In addition, experimental investigations are conducted to understand the complete reflector antenna system behaviours. Measurements show a good agreement with the simulation results. At last, the efficiency of the proposed frequency-dependent IWO (FDIWO) method both in bandwidth and optimality of the results are compared with original IWO method, common GO method and electromagnetic radiation (TICRA) software package. Comparison results show that the FDIWO method outperforms the other techniques.

1 Introduction

Reflector antennas are widely used for various applications such as satellite communications, radar systems and radio astronomy [1]. Shaped-reflector antenna is an excellent antenna for achieving cosecant-squared pattern in elevation and pencil beam in azimuth plane. In comparison with phased-array antennas, the main advantages of the reflector antennas are wide bandwidth and their simplicities which avoid using of expensive and weighty beam forming networks [2]. Several requirements on reflector antenna performances have demanded the development of sophisticated synthesis techniques.

The approaches available for reflector shaping are essentially of two types: geometrical optics (GO) and physical optics based. A useful set of references on these techniques can be found in [3]. Many techniques have been devised to obtain cosecant-squared radiation pattern in reflector antennas. Most of these methods are based on the principles of GO [4–9]. Several modifications of the GO-shaping methods have been proposed in the literature [10]. Different analysis methods for computing far-field patterns of the doubly curved reflector antennas have been presented [11, 12].

Invasive weed optimisation (IWO) has been found to be a simple but powerful algorithm for solving multi-dimensional, linear and non-linear optimisation problems with appreciable efficiency [13]. It has reportedly outperformed many types of evolutionary algorithms and other search heuristics when tested over both benchmark and real-world problems [14].

Recently, different electromagnetic applications of IWO such as, linear array antenna synthesis, design of a periodic thinned array antenna and the design of a U-slot patch antenna to have the desired dual-band characteristics are presented [15]. In [16] using IWO, the design of non-uniform, planar and circular antenna arrays that can achieve minimum sidelobe levels (SLLs) is presented. In [17], IWO has been employed to derive optimal dimensions of a patch antenna over a high impedance surface substrate. In [18], IWO algorithm is used to design a narrowband reflector antenna at 9.37 GHz. Other applications of IWO algorithm in antenna design problems are reported in [19–22].

In a previous work [23], using original IWO algorithm a cosecant-squared pattern reflector antenna fed by a pyramidal double-ridged horn (DRH) was synthesised at centre frequency 10 GHz and operates for 2–18 GHz range. A major drawback is that frequency variation effects were not incorporated in the process of reflector shaping. In fact, the reflector surface was synthesised by exploiting a frequency-independent algorithm. Owing to the single-frequency fitness function, the reflector surface was only optimised at the centre frequency and had no satisfactory radiation characteristics at other frequencies.

The aim of this paper is to introduce a frequency-dependent IWO (FDIWO) method for synthesising broadband cosecant-squared pattern reflector antennas. The proposed technique originates from the GO analysis and IWO algorithm including frequency-dependent fitness function. A low cross-polar 18–40 GHz conical DRH antenna without both pattern squint and pattern fluctuation is designed to illuminate the shaped reflector. In the first phase, using original IWO algorithm presented in a previous work [23], the reflector surface is synthesised at 29 GHz. As expected, the reflector antenna has not optimum radiation characteristics at other frequencies of the desired 18–40 GHz range. Then, in the second phase, FDIWO method using modified fitness function is proposed. In this phase, the reflector surface is synthesised using a more complex and accurate frequency-dependent fitness function including optimum weighting values. As a result of FDIWO method, a cosecant square pattern with a wide coverage beyond 40° over the entire 18–40 GHz operational bandwidth is achieved. Moreover, the ripple in the cosecant-squared region and the SLL is <0.7 and -26 dB, respectively.

Simulation results have been verified experimentally and excellent agreement is obtained. Finally, the designed reflector using FDIWO method, using previous method [23], using common GO method, also with physical optics-based software TICRA are compared with the improved performance of the design using FDIWO method. Based on the obtained results, the designed reflector antenna can be used in broadband surveillance-search radar systems.

2 Fundamentals of the antenna design

DRH is an excellent choice as a feed for reflector antennas as it provides low spillover, wide bandwidth, relatively high gain and very low-cross polarisation. In a previous work [23], a 2–18 GHz pyramidal DRH was used as a feed. The distortion of radiation patterns at higher frequencies and variable phase centre are the significant disadvantages of the conventional pyramidal DRH antenna. In this work, an 18–40 GHz conical DRH antenna is designed to illuminate the shaped reflector. The detailed design procedure of the conical DRH antennas is described in a prior work [24].

Doubly curved reflector antennas have two main sections. Central vertical section of the reflector must be designed to produce a shaped beam in the elevation plane. The transverse section is required to be a parabola for focusing the feed rays in the azimuth plane and consequently producing a narrow beam in that plane. The shape of the reflector antenna surface can be specified by combining both vertical and transverse curves. The conventional method for designing the shape of the reflector to produce a cosecant-squared pattern in the vertical plane is GO and is described in details by many authors [4–9]. Also a brief shaping procedure based on the GO is explained in the previous work [23].

3 Reflector surface synthesis using FDIWO

FDIWO is a hybrid optimisation algorithm that originates from classical IWO empowered with the GO method.

The FDIWO synthesis technique can be applied to produce various radiation patterns such as cosecant-squared pattern, pencil beams and contoured beams. It is believed that the scope of the application of this technique embraces the majority of commonly used reflector antenna configurations. The purpose of this paper is to introduce a FDIWO synthesis technique that can be used to synthesise broadband cosecant-squared pattern reflector antennas.

IWO is an ecologically inspired metaheuristic that mimics the process of weeds colonisation and distribution and is capable of solving multi-dimensional, linear and non-linear optimisation problems with appreciable efficiency [25]. The common IWO algorithm process is described in the previous work [23]. Fig. 1 shows an overview of the FDIWO synthesis technique.

As shown in [23], the differential equation of the central curve is given by

$$\frac{1}{\boldsymbol{\rho}(\varphi)}\frac{\mathrm{d}\boldsymbol{\rho}(\varphi)}{\mathrm{d}\varphi} = -\tan\left(\frac{\sigma(\varphi)}{2}\right) \tag{1}$$

where $\boldsymbol{\rho}(\varphi)$ is the radius vector from focal point to the central vertical section curve, φ is its angle of elevation, and $\sigma(\varphi)$ is the angle between the incident and reflected rays in the central vertical section. In the above equation, and $\sigma(\varphi)$ and $\boldsymbol{\rho}(\varphi)$ are both unknown. If $\sigma(\varphi)$ is specified then $\boldsymbol{\rho}(\varphi)$ can be determined. Therefore, the central curve can be obtained if the distribution of $\sigma(\varphi)$ between φ_1 and φ_2 is determined. The angular limits φ_1, φ_2 of the designed reflector correspond to the 10-dB points in the primary pattern at the centre frequency. Since the feed is placed with 15° offset and has about 64°10-dB beam width at the centre frequency (29 GHz), φ varies from $-17°$ to 47°. In the synthesis method described in the previous work [23], for approximating $\sigma(\varphi)$ distribution, various functions were examined to find a function with less parameters and fine accuracy. Accordingly, the following 5th order polynomial was chosen

$$\begin{aligned}\sigma(\varphi) = C_0 + C_1\varphi + C_2\varphi^2 \\ + C_3\varphi^3 + C_4\varphi^4 + C_5\varphi^5\end{aligned} \tag{2}$$

where C_i, $i = 0, 1, 2, 3, 4, 5$ are the coefficients to be determined. This polynomial is used in the FDIWO synthesis technique presented in this paper. Coefficients of this polynomial should be determined properly by means of FDIWO. To obtain these coefficients, the radiation pattern must be compared with the desired pattern. Consequently, fitness value of generated surface is the difference between the far-field elevation pattern and a desired cosecant-squared pattern. This procedure requires the repetitive computation of the fitness function at each iteration stage.

Defining the fitness function is the most significant step in the FDIWO synthesis procedure. The reflector surface is synthesised by exploiting a complex and accurate-weighted frequency-dependent fitness function as follows

$$F = \frac{1}{kl}\sum_{i=1}^{l} w_i \left[\sum_{j=1}^{m}\left(\left|P\left(f_i, \theta_j\right) - \csc^2\theta_j\right|\right)^2 + \sum_{j=m+1}^{k}\left(\frac{1}{2}\left(X_{ij} + \left|X_{ij}\right|\right)\right)^2\right] \tag{3}$$

where $X_{ij} = [P(f_i, \theta_j) - (-25)]$, $1 < m < k$, k and l are the number of sampling points and sampling frequencies, respectively, $P(f_i, \theta_j)$ is the radiated power, f_i is the ith sampling frequency and w_i represents the weighting value at the ith sampling frequency. In order to obtain the desired radiation characteristics over the entire 18–40 GHz operational bandwidth, several weightings have been applied. Fig. 2 shows the optimum weighting values against the frequency, obtained with numerous simulations.

The main feature that distinguishes this technique from others is the wide bandwidth. Owing to the

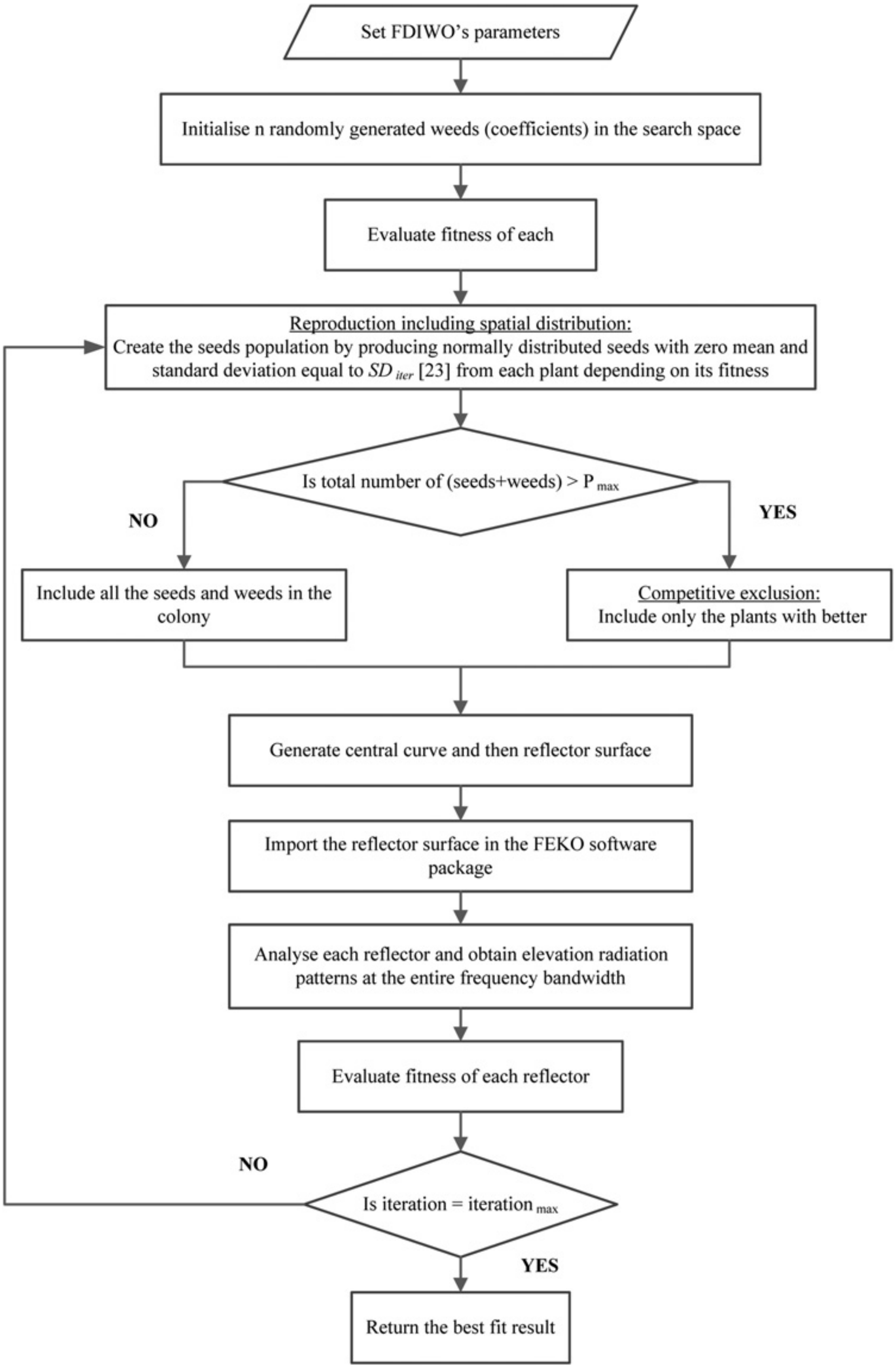

Fig. 1 *Flowchart of the FDIWO synthesis and optimisation technique*

frequency-dependent fitness function, the reflector antenna has optimised radiation characteristics at the entire 18–40 GHz range. Another feature that makes the current technique powerful is the flexibility to achieve low SLL and small pattern ripples simultaneously. Other optimisation algorithms, such as genetic algorithm (GA), particle swarm optimisation (PSO) and ant colony, are not often flexible enough to achieve desired SLL and ripple simultaneously. PSO is mainly used for sidelobe suppression [26, 27] and GA is applicable to synthesis of shaped beam for array antennas [28–31].

4 Results and discussion

4.1 Conical DRH antenna feed

In this section, we present the simulation and experimental results for the designed conical DRH antenna. To check the accuracy of simulations, we have compared the outcomes of both simulator packages HFSS and CST Microwave Studio. Closed results confirm the accuracy of simulations. In order to justify the results, the designed antenna was fabricated, tested and compared with the simulations. It was fabricated

doi: 10.1049/iet-map.2013.0406

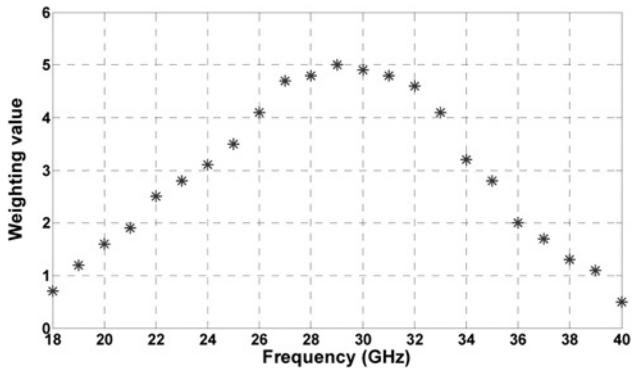

Fig. 2 *Optimum weighting values of the frequency-dependent fitness function*

with high precision (mechanical tolerance of 0.01 mm). Fig. 3*a* shows a picture of the fabricated antenna. The overall length and the radius of the conical DRH are 35.5 and 18.7 mm, respectively. The horn antenna and the double ridges are fabricated using, aluminum and copper, respectively. Copper is used for the ridges because of increased mechanical strength during machining. The simulated and measured voltage standing wave ratio (VSWR) of the designed antenna are presented in Fig. 3*b*. It is seen that maximum value of the VSWR is < 2.3 over the frequency range.

The measured co-polar and cross-polar far-field *E*-plane (*x–z* plane) and *H*-plane (*y–z* plane) radiation patterns of the designed feed horn at band edge frequencies are presented in Figs. 3*c* and *d*. The radiation patterns of these figures are obtained through HFSS. Although not shown, similar patterns were obtained through CST. In these figures, for the *E*-plane, E_θ-field and E_φ-field are co-polar and cross-polar components, respectively. For the *H*-plane, E_φ-field and E_θ-field are co-polar and cross-polar components, respectively. It can be observed that the proposed feed has symmetrical radiation patterns and low SLL over the entire frequency band. Specifically, the cross-polarisation level at boresight direction is considerably small. Since the induced cross-polarisation of the reflector depends on the feed, its cross-polarisation has a significant effect on the overall antenna cross-polar performance.

As mentioned before, the squint and fluctuation of radiation patterns at higher frequencies are the significant drawbacks of the pyramidal DRH antennas. The squint of the main beam is particularly a problem for reflector feeding which usually depends on a well-defined radiation pattern. However, for the designed conical DRH no such deterioration of the radiation patterns is seen.

Comparison of simulated and measured phase patterns of the DRH at centre frequency is presented in Fig. 4. The smooth variation of this phase pattern in illumination angle is of significance in the design of the shaped reflector. The discrepancy between theory and experiment is partly because of the test equipments.

4.2 Reflector antenna using frequency-independent fitness function

In the first step, the reflector surfaces are synthesised using the frequency-independent fitness function defined in [23]. The far-field elevation patterns of the final reflector surface generated in the 100th iteration at three typical frequencies

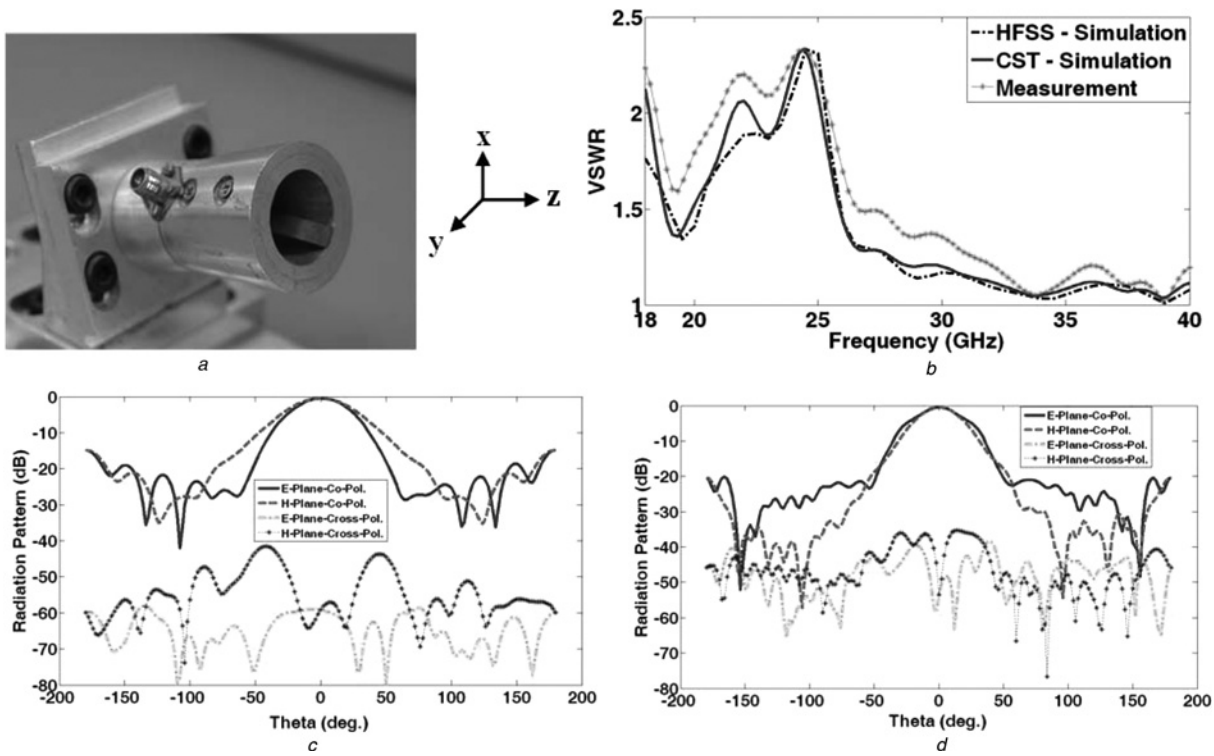

Fig. 3 *Designed feed horn and its radiation characteristics*

a Picture of the fabricated conical DRH antenna
b VSWR of the antenna
c Measured radiation patterns of the antenna at 18 GHz
d Measured radiation patterns of the antenna at 40 GHz

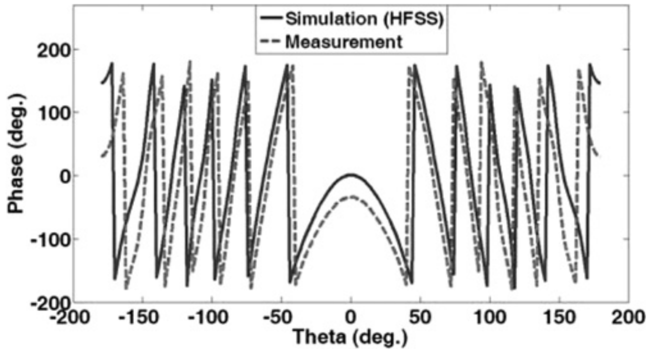

Fig. 4 *Simulated and measured phase patterns of the conical DRH at 29 GHz*

are presented in Fig. 5. The dashed line in this figure represents the desired pattern in the shaped region and maximum level of the sidelobe used to calculate the fitness function. It can be observed that the designed reflector has low ripples at the centre frequency. However, at band edge frequencies the ripples are considerable. Major drawback of this design is that frequency variation effects were not incorporated in the process of reflector shaping. Consequently, the reflector performances are only optimised at the centre frequency (29 GHz) and are not optimised at the entire bandwidth.

4.3 Improved reflector antenna using FDIWO method

In the second step, the reflector surfaces are synthesised by exploiting the modified frequency-dependent fitness function given in (3). Setup of the synthesis FDIWO method is given in Table 1. Fig. 6 shows convergence curve of the fitness function. After 100 iterations, lowest fitness and consequently the optimum solution are achieved.

The far-filed elevation patterns of the obtained surfaces at the centre frequency are shown in Fig. 7. It can be observed that the obtained patterns approach to the defined goal as the number of iteration increases.

The three-dimensional (3D) model of the complete designed reflector antenna system is presented in Fig. 8*a*. The antenna dimension and the focal length are 24.3×24.3 cm^2 and 18 cm, respectively. The placement of the horn is such that its phase centre is at the focal point of the reflector. Finally, the designed reflector antenna system was fabricated with a mechanical accuracy of $0.01\lambda_0$ and tested. Figs. 8*b* and *c* show the pictures of the fabricated antenna.

Table 1 FDIWO parameter values for the reflector synthesis

Symbols	Quantities	Values
N_0	number of initial population	30
k	number of sampling points	50
l	number of sampling frequencies	23
$\mathrm{Iter}_{\max}$	maximum number of iterations	100
dim	problem dimension	6
$P_{\max}$	maximum number of plant population	10
$s_{\max}$	maximum number of seeds	6
$s_{\min}$	minimum number of seeds	1
n	non-linear modulation index	3
$\mathrm{SD}_{\mathrm{initial}}$	initial value of standard deviation	10
$\mathrm{SD}_{\mathrm{final}}$	final value of standard deviation	0.1
$x_{\text{ initial}}$	initial search area	$-3 < x_{\mathrm{initial}} < 3$

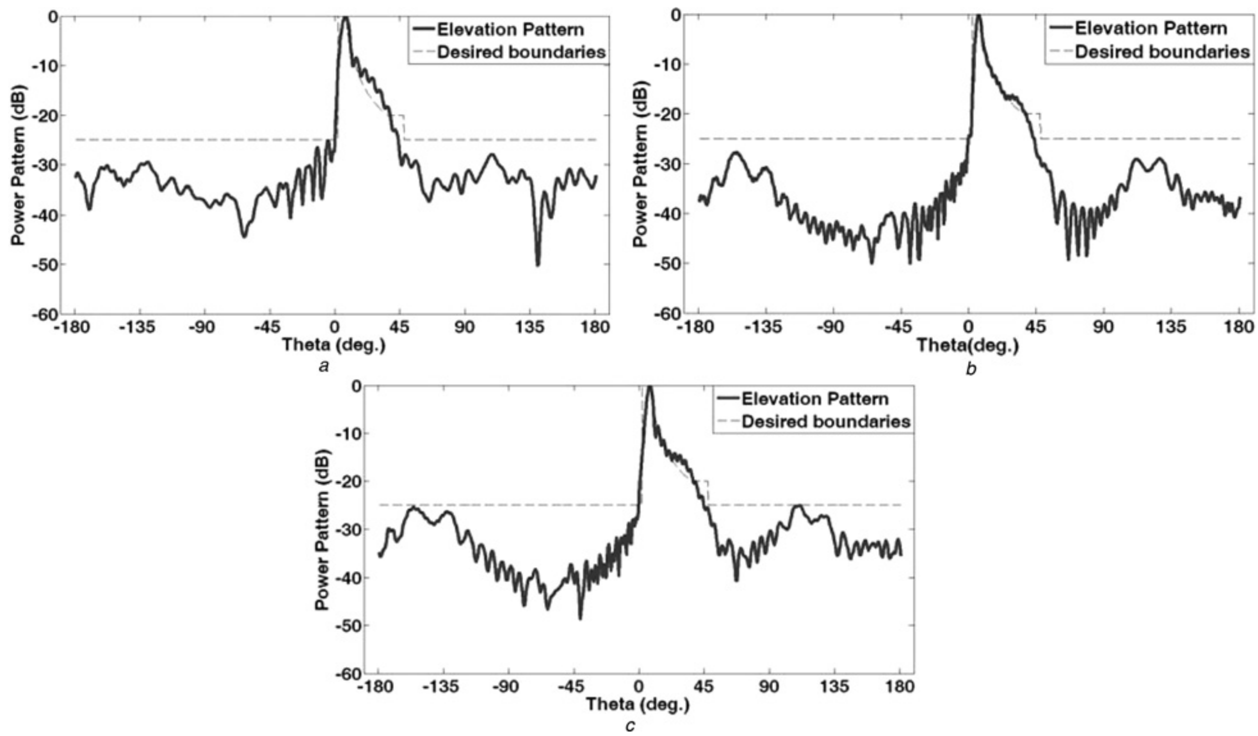

Fig. 5 *Far-field elevation patterns of the reflector synthesised using the frequency-independent fitness function at*

a 18 GHz
b 29 GHz
c 40 GHz

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doi: 10.1049/iet-map.2013.0406

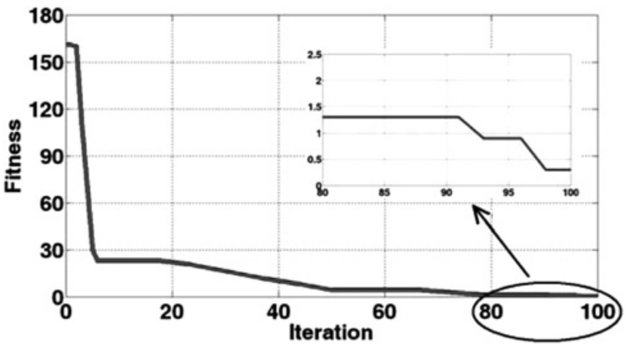

Fig. 6 *Convergence curve of the fitness function*

The simulated and measured far-filed patterns of the improved antenna at centre and band edge frequencies are presented in Figs. 9 and 10. It can be observed that the designed antenna has satisfactory radiation patterns with small ripples in the cosecant-squared region and low SLL over the entire frequency band. Moreover, the designed reflector antenna has a cross-polarisation level about 50 dB lower than the co-polarisation level at bore sight in all of the measured radiation patterns. Both the SLL and the ripple are lower than those provided by reflector antenna synthesis using the frequency-independent fitness function.

The measured gain, ripple and the SLL of the reflector at several typical frequencies are presented in Table 2. It can be seen that the gain of the antenna increases as frequency

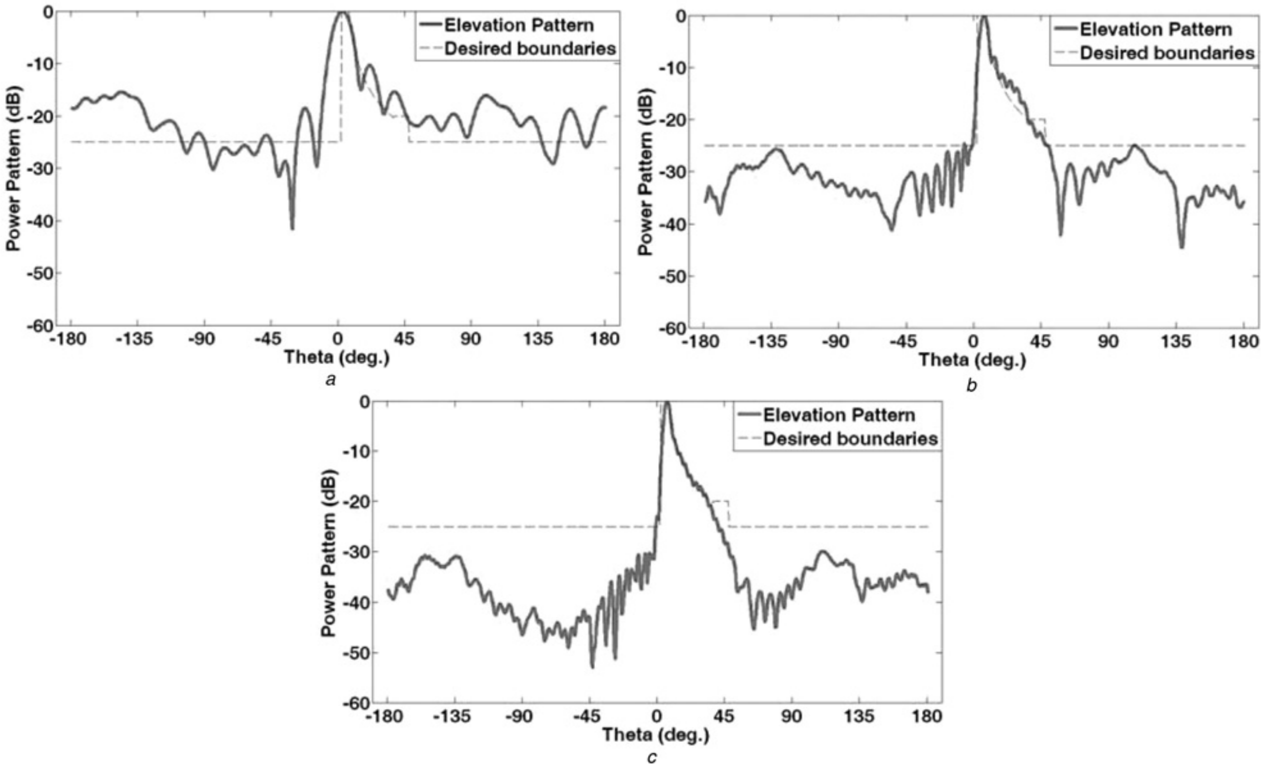

Fig. 7 *Elevation radiation patterns of the generated reflector surfaces*

a In the first iteration
b In the 50th iteration
c Elevation pattern of the final optimum reflector surface generated in the 100th iteration

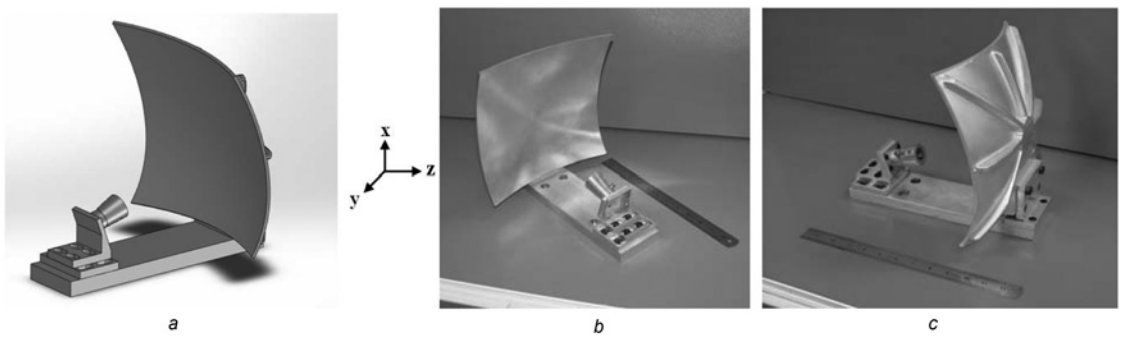

Fig. 8 *Improved reflector antenna*

a Three-dimensional model of the complete improved reflector antenna system
b Overall view of the fabricated antenna
c Side view of the fabricated antenna

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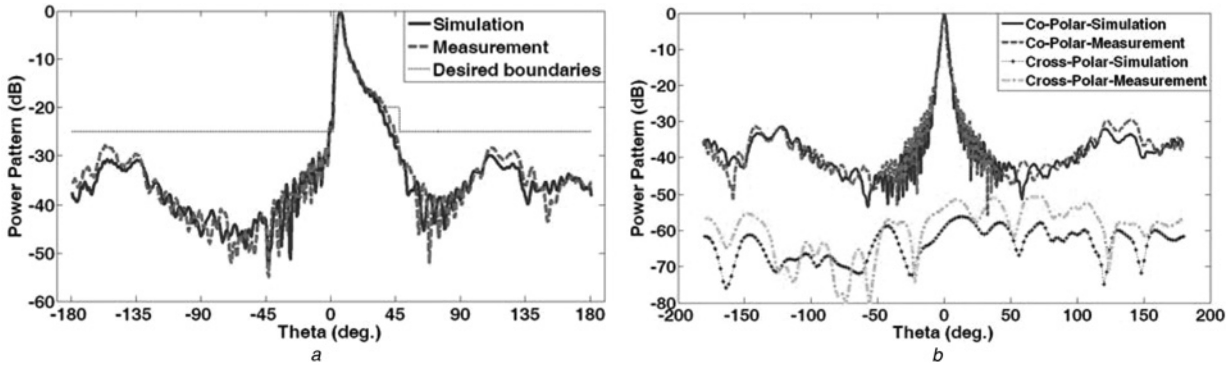

Fig. 9 *Simulated and measured far-filed patterns of the improved antenna at centre frequency (29 GHz)*

a Elevation pattern
b Azimuth pattern

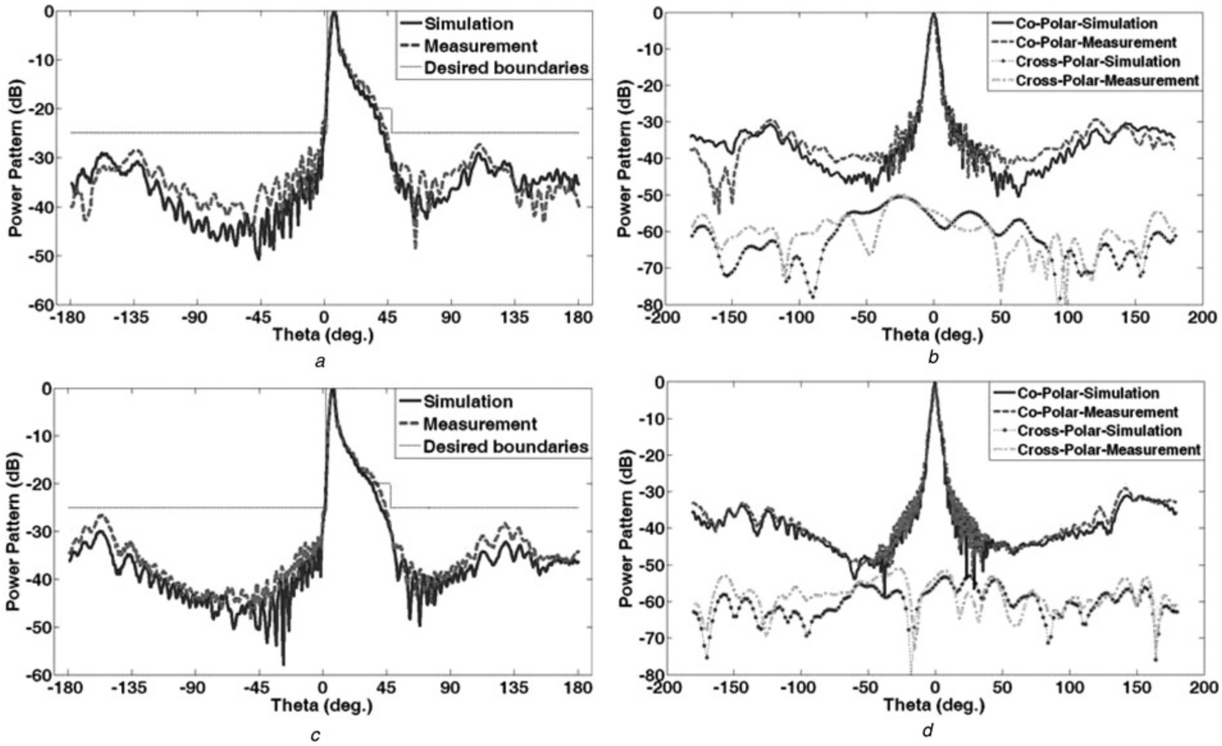

Fig. 10 *Simulated and measured far-filed patterns of the improved antenna at band edge frequencies*

a Elevation pattern at 18 GHz
b Azimuth pattern at 18 GHz
c Elevation pattern at 40 GHz
d Azimuth pattern at 40 GHz

increases. The antenna peak gain is 31.3 dB and occurs at the end of the frequency band (40 GHz). Moreover, the ripple in the cosecant-squared region and the SLL is < 0.7 and -26 dB, respectively.

Fig. 11*a* indicates the general shape of the coverage required in the elevation plane for the ground-based air-surveillance system, where R, h and θ are the distance between the target and receiving antenna, the target's height and the elevation angle, respectively. The angular width of the elevation patterns of the designed antenna in the $\csc^2\theta$ region is approximately 40°. Fig. 11*b* depicts the calculated received power against distance for $h = 10$ km. As shown in this figure, the received power is constant for, 15 km $< R <$ 114 km, but with the increase of the distance, the received power decreases.

Finally, an extensive performance comparison of the FDIWO method, original IWO, common GO method and

Table 2 Measured gain, ripple and SLL of the improved reflector antenna against frequency

Frequency, GHz	18	24	29	34	40
Maximum gain, dB	28.5	29.2	29.8	31	31.3
Ripple, dB	0.7	0.6	0.4	0.5	0.5
SLL, dB	–28	–27.8	–27.7	–27.1	–26.4

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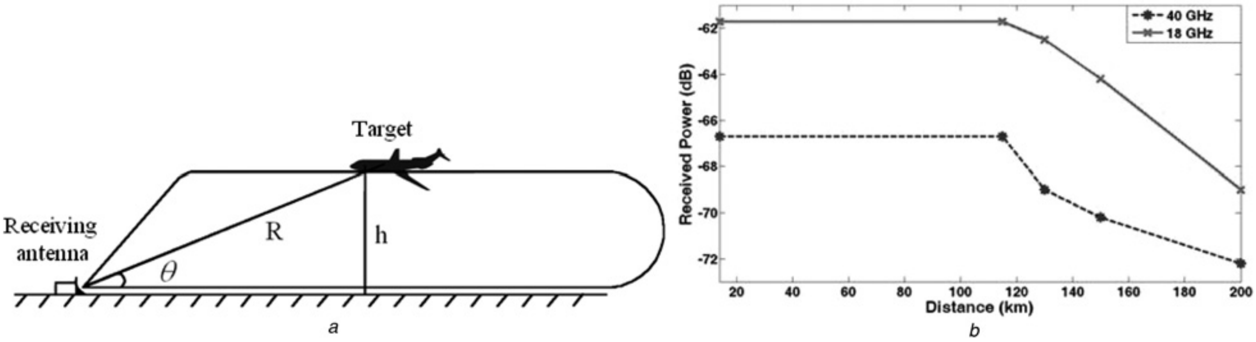

Fig. 11 *Distance between the target and receiving antenna*

a Beam from ground-based antenna providing coverage on target
b Received power by the designed cosecant-squared pattern reflector antenna

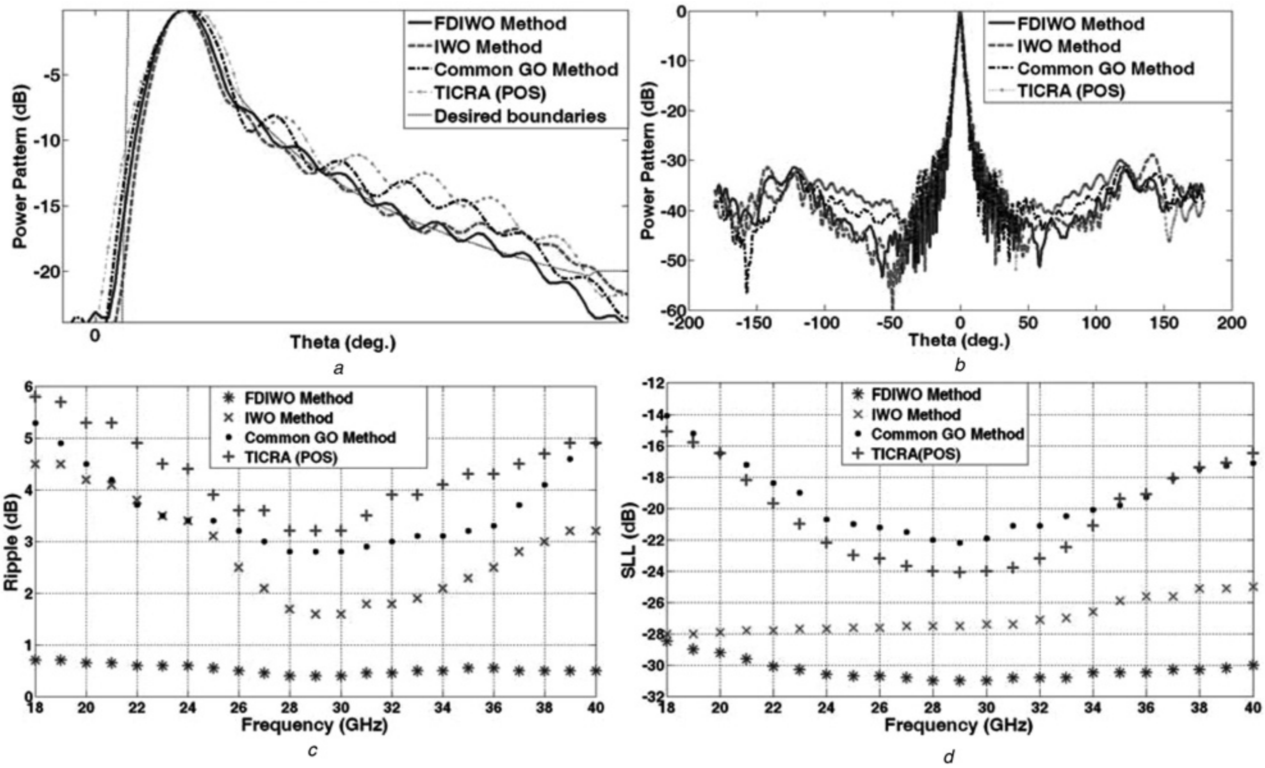

Fig. 12 *Comparison of four methods*

a Elevation radiation patterns at centre frequency
b Azimuth radiation patterns at centre frequency
c Ripple against frequency
d SLL against frequency

TICRA CAD tool is performed. The radiation patterns at centre frequency, the ripple and the SLL against frequency obtained by four methods are depicted in Fig. 12. Compared with the other methods, the proposed FDIWO method allows to obtain smaller ripples in the shaped region and lower SLL. Specifically, at low and high frequencies of the bandwidth, other methods do not show adequate performance.

5 Conclusion

This paper presents a FDIWO method for synthesising broadband cosecant-squared pattern reflector antennas. FDIWO is a hybrid optimisation algorithm that originates from classical IWO combined with the GO method. A proper fitness function is used as the most significant step in the FDIWO synthesis procedure.

In the first step, using a simple frequency-independent fitness function the reflector surface is synthesised at 29 GHz and operates for 18–40 GHz. Therefore suitable radiation characteristics are obtained at centre frequency of the 18–40 GHz range, whereas the synthesised reflector has not satisfactory performances at other frequencies. In the second step, the reflector surface is synthesised by exploiting a complex and accurate-weighted frequency-dependent fitness function. The reflector antenna synthesised using FDIWO method has desired radiation characteristics at the entire 18–40 GHz range. Simulation results have been checked experimentally and excellent agreement is obtained.

A low cross-polar 18–40 GHz conical DRH antenna without both pattern squint and pattern fluctuation is designed to illuminate the shaped reflector. It was found that for satisfactory antenna performance, high mechanical accuracy and small geometrical tolerances of the feed horn and reflector are essential.

The main feature that distinguishes FDIWO method from others is the wide bandwidth. Moreover, compared with the previous methods, the proposed method allows to obtain extremely smaller ripples in the shaped region and lower SLL.

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doi: 10.1049/iet-map.2013.0406