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Very-low-sidelobe printed tapered arc-shaped wide-slot antenna array

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Abstract: This study proposes two unique techniques to increase the impedance bandwidth and reduce the sidelobe level (SLL) of printed antenna arrays. In the first, a printed tapered wide-slot antenna array fed by an array of printed patch elements placed above a metal reflector is introduced. The impedance bandwidth of this antenna array is 10.3–23.1 GHz, that is, 76.6%. By tapering the width of each of the slot elements, a very low SLL of −33.5 dB is obtained. The proposed antenna has a stable radiation pattern over the range 14.7–17 GHz, that is, the 3 dB gain bandwidth is 14.5% and has a front-to-back ratio (F/B) level of 40 dB and a low cross-polar component <−45 dB at broadside and <−35 dB off-broadside direction. In the second technique, to achieve further improvement in the SLL of the antenna array the length of each of the slot array elements is tapered, in the form of an arc-shape, leading to an antenna array with very low SLL of −35 dB at a centre frequency of 16.26 GHz, a wide bandwidth of 78.8%, 20 dB SLL bandwidth of 8.8%, and high F/B of 38 dB. A prototype of the antenna array is fabricated and the simulated and measured results are presented and discussed.

1 Introduction

Printed antenna arrays are usually used in telecommunication systems such as point to point and point to multipoint and in microwave and millimeter-wave radar systems [1]. They have numerous attractive features in terms of light weight, small size, low cost, high efficiency and ease of fabrication and installation, and in array designs the microstrip feed network can be placed on the same substrate as the microstrip patches [1, 2]. In radar systems, parameters such as sidelobe level (SLL), front-to-back ratio (F/B), [1, 2] and bandwidth, [3] are of high importance. Depending on the radar system, an SLL between −20 and −50 dB is usually required [2].

With printed antennas, the realisation of arrays with SLL lower than −25 dB becomes increasingly difficult mainly because of: mutual coupling between radiating elements, surface wave effects, parasitic radiation from the feeding network and tolerances in fabrication [1, 2]. There are usually two types of arrays in microstrip structures, namely, the corporate-fed and the series-fed patch antenna arrays, both of which are inherently narrow in bandwidth. The discontinuities, bends, power dividers and other components in the corporate-fed array cause spurious radiation that limits the minimum achievable SLL [2]. The structure of a series-fed array is such that it uses shorter line lengths in comparison with corporate-fed arrays, and this leads to an antenna with less space on substrate, lower attenuation loss, and spurious radiation from feed lines [4]. However, for large series-fed arrays, amplitude and phase tracking with frequency can be problematic [5].

To reduce the SLL in printed antenna arrays, several approaches have been proposed, such as the use of the following: a corner reflector (i.e. a non-planar structure) to shield the feed network from the main radiating elements leading to −32 dB in SLL [1]; coaxial probes along with phase shifters to reduce SLL to almost −35 dB [2]; a feed network behind the ground and connected to the antenna via pins [6]; aperture-coupled patch antennas [7, 8]; and a waveguide-fed microstrip patch array at 76 GHz [9, 10]. By extending the finite ground plane in between the Yagi-like antenna elements, [11], and the double-dipole antenna elements, [12], low-sidelobe linear series-fed endfire arrays have been reported. It is worth mentioning that in these two papers no attempt was made to increase the impedance bandwidth of the antenna array structures.

Bandwidth enhancement in patch antenna arrays is mostly based on stacking patches on top of each other [13] or placing parasitic elements beside the patch antenna [14]. There is, however, no mention of the SLL performance in those papers dealing with such array structures. Based on the literature review done by the present authors, it seems that most of the works published are either on increasing the bandwidth or improving the SLL of the array, but not both together. The improved SLL structures published are either very complex or are non-planar in structure. In a recent study [15], a simple method to increase the bandwidth and reduce the SLL of the printed antenna array is proposed. It is shown that by using a slot in the ground plane of a conventional series-fed patch antenna array, a wideband (BW of order 76%) and low-sidelobe (SLL of −32.5 dB) antenna array can be obtained.

Motivated by the aforementioned issues and based on the method that is proposed in [15] two unique techniques are introduced in this paper to further improve the SLL of the printed antenna array. To do so, a printed tapered wide-slot antenna array fed by an array of printed patch elements placed above a metal reflector is introduced leading to wide impedance bandwidth along with low SLL and high F/B. The tapering of the slot elements is carried out by changing the width of each element. Further improvement in the SLL of the proposed antenna array is achieved by tapering the width and length of each slot array elements simultaneously. To this end, a linear tapered arc-shape wide-slot antenna array (LTASA) that is excited with a series-fed printed antenna array along with a reflector placed above the patches is presented. The proposed printed tapered wide-slot antenna arrays are analysed by means of a commercially available full-wave finite-element electromagnetic (EM) simulator, Ansoft's HFSS.

2 Antenna design and structure

The aim of this work is to design a uni-directional low-SLL, wide bandwidth printed wide-slot antenna array. As is well documented in the literature, a slot antenna if appropriately fed, that is, has a tapered aperture field distribution, will have a low SLL, and a wide printed slot antenna can provide a large impedance bandwidth. A series-fed printed antenna array with proper Chebyschev distribution can produce a suitable tapered field distribution. Thus, one can use such a series-fed printed antenna array as the feed system for a linear wide-slot printed antenna array. Such a structure can provide a low SLL and wide band impedance bandwidth antenna array. Since tapering an array of antenna elements results in lowering of SLL, this idea can be applied to the slot array of the above structure, that is, the width of the slots in the linear direction can be tapered to further improve the SLL of the array. Also, further improvement in SLL of the proposed antenna array can be achieved by tapering the width and length of each slot array elements simultaneously. These two ideas are the base of this work to design a low SLL and wide bandwidth antenna array.

The proposed low-sidelobe antenna array design follows these steps: (i) design of a conventional printed series-fed patch antenna array, referred to as the feeding network to provide a tapered amplitude distribution to achieve low SLL, (ii) design of a linear tapered wide-slot antenna array, LTSA, (iii) optimisation of the proposed antenna array for high F/B, low SLL and wide impedance bandwidth and (iv) design of a LTASA and optimisation of the proposed antenna array to achieve the minimum SLL.

The schematic of the proposed antenna array, LTSA, is shown in detail in Fig. 1. The array contains 22 similar square patch elements of side $a = 5.6$ mm each, placed on a grounded substrate of $\epsilon_r = 2.2$ and thickness of 0.508 mm. The size of the substrate is $L = 310$ mm and $W = 20$ mm. The corner-fed square patch is chosen because it provides high input impedance, making it well suited for a series-fed patch array. The array is of resonant type and is designed for radiation in the broadside direction. The design centre frequency is 16.26 GHz. The antenna array is split into two linear sub-arrays and fed in the middle. This symmetric arrangement further improves the cross-polarisation level of the array and prevents the beam-pointing direction from varying with frequency [16]. As such, the cross-polar component generated in one side of the array is cancelled by the cross-polar component generated in the opposite side of the array for the boresight direction. In order to obtain a boresight pattern, the spacing between the feed points of the array elements must be set at one guided wavelength, λ_g, to ensure an equal phase between the elements. The antenna array has been designed for a −40 dB SLL through an appropriate Chebychev taper distribution. A tapered distribution is readily obtained using quarter-wavelength transformers along the line. After obtaining the amplitude coefficients, the ratio n, between amplitude of any two neighbouring elements is calculated. According to [17, 18], the square root of this ratio gives the relative characteristic impedance of the two connected quarter wave lines, $n^{1/2} = Z1/Z2$. For the first seven elements, two $\lambda_g/4$ transformers along with a $\lambda_g/2$ transformer are used. The characteristic impedance of the $\lambda_g/4$ line closer to the $\lambda_g/2$ line can be set equal to each other and the value for the other $\lambda_g/4$ line can be calculated based on the mentioned ratio. This would result in less spurious radiation from such discontinuities. Unlike the first seven elements, for elements 7 to 11, instead of $\lambda_g/2$ lines, two $\lambda_g/4$ transformers are used (in this way, for the last array elements the size of the feed lines would be physically large enough to be constructed). The above ratio, $n^{1/2}$, between any two neighbouring elements now should be considered for two pairs of $\lambda_g/4$. For each pair, one can consider a ratio $n^{1/4}$ between the two $\lambda_g/4$ lines and as before can assume a value for one of the $\lambda_g/4$ lines and calculate the characteristic impedance for the other line. Of course, the value chosen for the line should be such that the characteristic of the other line would be physically possible to fabricate. Overall, the characteristic impedance of the half-wave lines is set at 115 Ω while those of the quarter-wave transformers are between 80 and 125 Ω. The detailed design considerations for series-fed patch arrays are discussed in [17, 18]. Knowing the characteristic impedances of the lines, one can then calculate the line widths and lengths between array elements.

This feeding network is exploited to provide a tapered amplitude distribution on the LTSA. Through optimisation, the length of the slot elements is $L_s = 13$ mm ($\simeq \lambda_g$) and its width, W_s, changes according to a linear tapering format from the size of 11 mm at the ends of the array to 13 mm at the centre of it. Table 1 summarises the widths of each of the slot array elements.

As shown in Fig. 2, the slot is positioned $t = 0.2$ mm from the main feed line, and a 50 Ω microstrip line with $W_f = 1.53$ mm is used to feed the array. Since this structure is a bi-directional radiator, one can place a reflector of same dimension as that of the substrate above the printed patch elements to make the radiation uni-directional. The reflector-to-patch spacing is set at $g = 1.5$ mm.

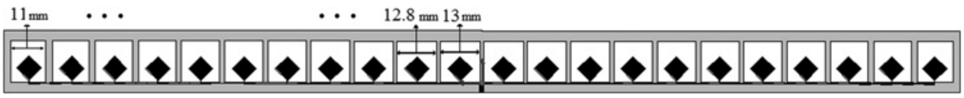

Fig. 1 *Structure of the proposed antenna showing array of tapered slots fed by array of series-fed patch elements*

Table 1 Widths of the slot array elements

slot's number (from centre to end of the array)	1	2	3	4	5	6	7	8	9	10	11
slot's widths, mm	13	12.8	12.6	12.4	12.2	12	11.8	11.6	11.4	11.2	11

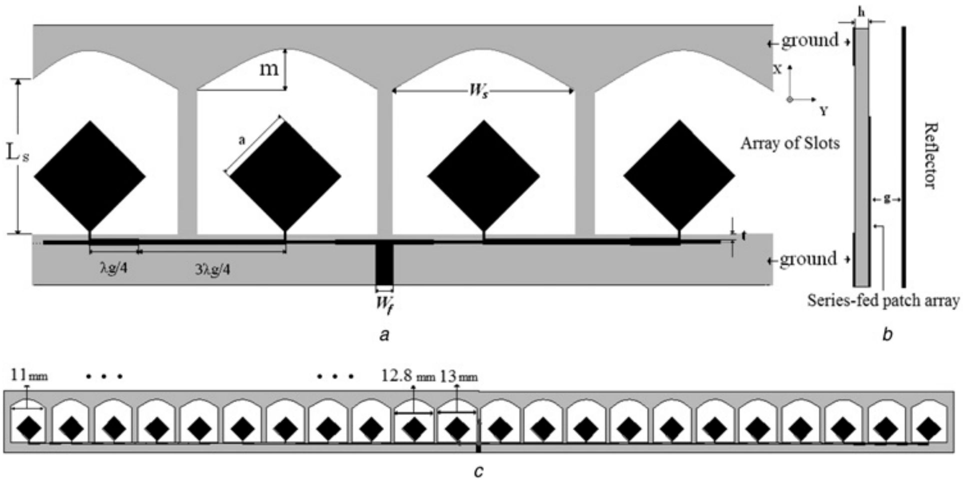

Fig. 2 *Structure of the proposed tapered arc-shaped wide-slot antenna array*

a Central elements of the array
b Side view
c Overall top view

To further improve the SLL, an LTASA antenna is proposed. In this structure in addition to tapering the widths of the each slot array elements, as discussed before, the length is also tapered through a half-cycle of a sinusoidal curve with the maximum of $m = 3$ mm, as depicted in Fig. 2*a*. This results in a lower SLL. As before, the LTASA also has a reflector spaced at $g = 1.5$ mm. In the following section the simulation, via the software package HFSS, and measured results are presented.

3 Results and discussions

In this section, detailed simulation and experimental results of the proposed antenna arrays are presented. In the first part, the printed tapered wide-slot antenna array fed by an array of printed patch elements placed above a metal reflector, LTSA, shown in Fig. 1, is investigated, and in the second part, the low-sidelobe tapered arc-shape wide-slot antenna array, LTASA, as shown in Fig. 2, is analysed.

3.1 Low-sidelobe printed tapered wide-slot antenna array, LTSA

The simulated as well as the measured reflection coefficient of the LTSA antenna array is shown in Fig. 3. The results show that the proposed antenna has a wide impedance bandwidth, ranging from 10.3 to 23.1 GHz, that is 76.6%. In comparison with the antenna investigated in [4], the impedance bandwidth of the proposed antenna has increased by a factor of almost 24. Through simulations it is seen that the proposed antenna has a stable radiation pattern over the 14.7–17 GHz, that is the 3 dB gain bandwidth is 14.5%. In this range, the radiation pattern has a pencil beam shape, but out of this range the pattern splits because the feed lines are no longer quarter-wave transformers, leading to changes in amplitude and phase of the signals at each of the patches, and hence changing the electric field distribution on the slot that causes the pattern to have nulls in the broadside direction.

Fig. 4 shows the simulated and measured E- and H-plane radiation patterns of the LTSA antenna. From this figure it

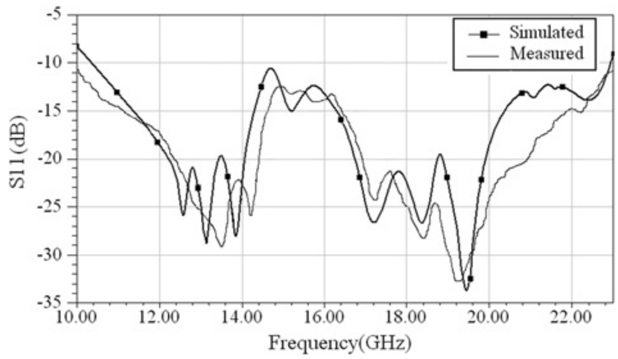

Fig. 3 *Simulated and measured reflection coefficient of the low-sidelobe tapered printed wide-slot antenna array*

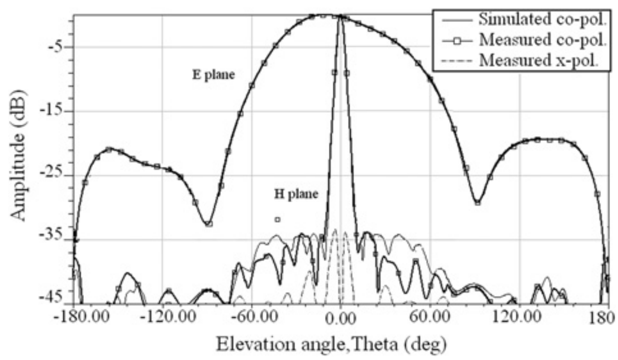

Fig. 4 *Simulated and measured radiation pattern (E- and H-plane) of the low-sidelobe tapered printed wide-slot antenna array at 16.26 GHz*

can be seen that the proposed antenna has a good directional pattern with −33.5 dB SLL and 4.5° half-power beam width (HPBW) at the centre frequency. It should be said that if equal-sized slot array elements are used, the SLL would be −32.5 dB, and thus, some 1 dB improvement would have been achieved through tapering the slot array elements lengths. Moreover, the proposed antenna has 40 dB of F/B level and a low cross-polar component <−45 dB at broadside and <−35 dB off-broadside direction. At the beam peak, the proposed antenna has maximum co-polarisation gain of 18.2 dBi at broadside direction at centre frequency. Through simulations it is seen that frequency range over which the proposed antenna has an SLL <−20 dB is 15.5–16.5 GHz which is 6.2%.

3.2 Low-sidelobe printed tapered arc-shape wide-slot antenna array, LTASA

The antenna array discussed in the previous section through tapering the width of each of the slot array elements can provide wide impedance bandwidth as well as low SLL and high F/B. To reduce the SLL even further, the length of slot array elements can also be tapered. As such, in this section, detailed simulation and experimental results of the low-sidelobe LTASA, are presented.

Fig. 5 shows the simulated as well as the measured reflection coefficient of the proposed antenna array structure. This shows that the antenna has wide impedance bandwidth of 82% ranging from 10 to 23 GHz, for $|S_{11}| < -10$ dB. In comparison with the antenna investigated in [4], the impedance bandwidth of the proposed antenna has increased more than 24 times but in comparison with the antenna array of the previous section it does not change significantly. Through simulations it is seen that the proposed antenna has a stable radiation pattern over the 14.6–17.1 GHz, that is the 3 dB gain bandwidth is 15.8%. In this range, the radiation pattern has a pencil beam shape, but out of this range the pattern splits similar to that of the previous section.

The simulated and measured far-field E-plane (x–z plane) and H-plane (y–z plane) radiation patterns at the centre frequency are shown in Fig. 6. The measured far field H-plane radiation patterns at three different frequencies over the bandwidth are shown in Fig. 7. From these figures it can be seen that the proposed antenna has a very good uni-directional radiation pattern with −35 dB SLL and a HPBW of 4.5°. Compared with the conventional series-fed antenna array, [15], and the antenna array investigated in the previous section, more than 10 and 1.5 dB improvements in SLL are observed, respectively. The

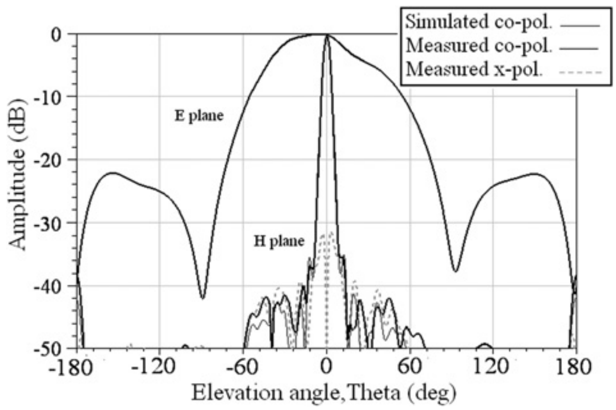

Fig. 6 *Simulated and measured E-plane (x–z plane) and H-plane (y–z plane) co-polar, and measured H-plane cross-polar radiation pattern of the low-sidelobe tapered arc-shaped wide-slot antenna array at 16.26 GHz*

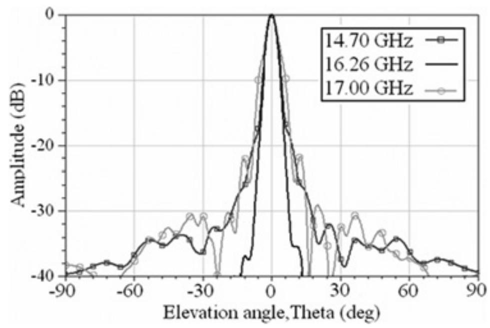

Fig. 7 *Measured H-plane (y–z plane) co-polar radiation pattern of the low-sidelobe tapered arc-shaped wide-slot antenna array for three different frequencies over the bandwidth*

frequency range over which SLL <−20 dB is found to be 15.2–16.6 GHz which is 8.8%.

Additionally, the simulated and measured results show that SLL <−30 dB can be achieved over a wide operating bandwidth, 16–16.4 GHz. It is also noticed that the cross-polarisation level is quite low at broadside, that is, <−40 dB and is <−33 dB off broadside. The main beam of the antenna has a maximum co-polarisation gain of 18.1 dBi. The proposed antenna has more than 38 dB F/B level.

As is well known, in order to achieve a high level of EM coupling to the feed-line, a large slot size is normally used in the antenna. Therefore any variation in feed shape or slot shape will change the coupling property; thus, the operating bandwidth and, in the array configuration, SLL are governed by the impedance match between the feed shape and the ground-plane slot. On the other hand, an optimum performance can be obtained when the feed and slot shapes

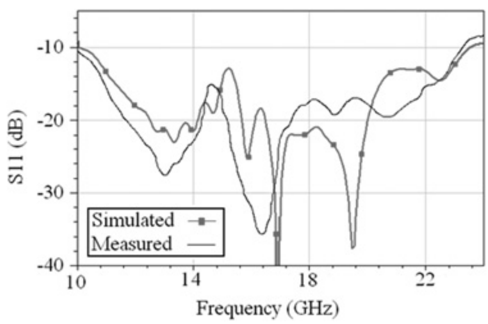

Fig. 5 *Simulated and measured reflection coefficient of the low-sidelobe tapered arc-shaped wide-slot antenna array*

Table 2 Performance of the low-sidelobe tapered arc-shaped wide-slot antenna array for various *m*

m, mm	1	2	3	4	Rectangular slot (13×13.5 mm^2)
SLL, dB	−32	−33.5	−35	−34	−31.5
impedance bandwidth, %	78	79.6	82	85	80.2
F/B, dB	40	39	38	38	37

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are appropriately selected. Therefore an arc-shaped slot is selected instead of simple rectangular-shaped slot to achieve the best SLL and bandwidth. Table 2 summarises the effect that *m* has on SLL, bandwidth and F/B of the antenna. The results show that the F/B is not very sensitive to change in the *m*, but parameters such as SLL and impedance bandwidth are affected.

4 Conclusion

By placing a simple array of slots in the ground plane of a series-fed microstrip antenna array and optimising the dimensions, a simple method to simultaneously increase the impedance bandwidth, reduce the SLL, and increase F/B has been proposed. The antenna array structure has 78.8% of impedance bandwidth for $S11 < -10$ dB. The 3 dB gain bandwidth of the proposed antenna is 15.8%. The gain is almost stable over the bandwidth. The structure can have a -30 dB of SLL and 38 dB of F/B over 16–16.4 GHz. The method of placing a slot in the ground plane of the series-fed microstrip antenna array results in a very low cross-polarisation, < -33 dB. Moreover, the antenna structure is planar in configuration, easy to design and fabricate and can be performed in both linear and planar printed antenna arrays. These features make it suitable for low-SLL radar applications.

5 References

1 Nesic, A., Micic, Z., Jovanovic, S., Randonvic, I.: 'Millimeter wave printed antenna array with high side lobe suppression'. Proc. IEEE AP-S Int. Symp, 2006, pp. 3051–3054

2 Pozar, D.M., Kaufman, B.: 'Design considerations for low sidelobe microstrip arrays', *IEEE Trans. Antennas Propag.*, 1990, **38**, (8), pp. 1176–1185

3 Skolnik, M.I.: 'Radar handbook' (McGraw Hill Press, 2008, 3rd edn.), ch. 1, p. 8

4 Pozar, D.M., Schaubert, D.H.: 'Comparison of three series-fed microstrip array geometries'. Proc. IEEE AP-S Int. Symp., 1993, vol. 2, pp. 728–731

5 Pozar, D.M.: 'A review of bandwidth enhancement techniques for microstrip antennas', in D.M. Pozar and D.H. Schoubert 'Microstrip antennas: analysis and design of microstrip antennas and arrays' (IEEE Press, 1995), pp. 157–166

6 Gronau, G., Moschuring, H., Wolff, I.: 'Microstrip antenna arrays fed from the backside of the substrate'. Proc. Int. Symp. Antennas Propagation, Kyoto, Japan, 1985

7 Pozar, D.M.: 'A microstrip antenna aperture coupled to a microstrip line', *Electron. Lett.*, 1985, **21**, pp. 49–50

8 Pozar, D.M., Jackson, R.W.: 'An aperture coupled microstrip antenna with a proximity feed on a perpendicular substrate', *IEEE Trans. Antennas Propag.*, 1987, **35**, pp. 728–731

9 Hirokawa, J., Ando, M.: 'Sidelobe suppression in 76 GHz post-wall waveguide-fed parallel plate slot arrays', *IEEE Trans. Antennas Propag.*, 2000, **48**, (11), pp. 1727–1732

10 Kimura, Y., Takahashi, M., Haneishi, M.: '76 GHz alternating-phase fed single-layer slotted waveguide arrays with suppressed sidelobes in the E-plane', *IEEE Trans. AP-S, Digest*, 2003, **41**, pp. 1042–1045

11 Bayderkhani, R., Hassani, H.R.: 'Wideband and low sidelobe linear series fed Yagi-like antenna array', *Prog. Electromagn. Res. B*, 2009, **17**, pp. 153–167

12 Bayderkhani, R., Hassani, H.R.: 'Low sidelobe wideband series fed double dipole microstrip antenna array', *IEICE Electron. Express*, 2009, **6**, (20), pp. 1462–1468

13 Targonski, S.D., Waterhouse, R.B., Pozar, D.M.: 'Wideband aperture coupled stacked patch antenna using thick substrates', *Electron. Lett.*, 1996, **32**, pp. 1941–1942

14 Oh, S., Seo, S., Yoon, M., Oh, C., Kim, E., Kim, Y.: 'A broadband microstrip antenna array for LMDS applications', *Microw. Opt. Lett.*, 2002, **32**, (1), pp. 35–37

15 Bayderkhani, R., Hassani, H.R.: 'Wideband and low sidelobe slot antenna fed by series-fed printed array', *IEEE Trans. Antennas Propag.*, 2010, **58**, (12), pp. 3898–3904

16 Vallencchi, A., Gentili, G.B.: 'Design of dual-polarized series-fed microstip arrays with low losses and high polarization purity', *IEEE Trans. Antennas Propag.*, 2005, **53**, pp. 1791–1798

17 James, J.R., Hall, P.S.: 'Handbook of microstrip antennas' (Peter Peregrinus Ltd., 1989), pp. 645–665

18 Garg, R., Bhartia, P., Bahl, I., Ittipiboon, A.: 'Microstrip antenna design handbook' (Artech House, Norwood, MA, 2001)