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Suppression of grating lobes from a corrugated 2 × 2 slot antenna array with element spacing beyond a wavelength

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Abstract: A method of loading surface corrugation in a 2 × 2 slot planar array with element spacing in the *E* plane beyond a wavelength is proposed for suppressing high grating lobes. This antenna array adopts a corrugated structure as a secondary radiation source to make effective spacing of elements within a wavelength. The authors investigate numerically and experimentally the performance of the antenna, and find good agreement between the measured and simulated results. Compared with conventional flat 2 × 2 slot arrays, the results show that the gain of the corrugated slot antenna array is significantly improved by about 6 dB, the half-power beamwidth is narrowed by 12° in the *E* plane and 10° in the *H* plane and the high grating lobe level occurring in the *E* plane of the flat slot array is sharply suppressed as well. Moreover, it is found that the introduction of a secondary source in this slot array can also make the element spacing in the *H* plane larger than a wavelength without an obvious grating lobe. The radiation mechanism of this antenna is well described and the role of surface corrugation in this antenna is demonstrated as the secondary radiation source which is responsible for the improved antenna gain and suppressed grating lobe.

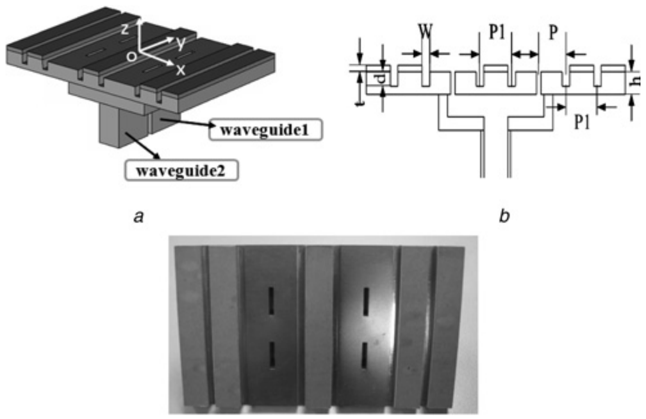
1 Introduction

In the design of antenna arrays, the element spacing is often required to be within a wavelength to avoid a high grating lobe [1]. In 2005, Leger *et al.* [2] adopted electromagnetic (EM) band gap material to cover a patch array with element spacing larger than a wavelength, and obtained a very low grating-lobe and high directivity, unexpectedly breaking the limitation of elements distribution in the standard antenna array. In our latest work [3], we presented another method of constructing secondary radiation sources between elements to reduce high grating lobe in the linear slot array. The secondary source is composed of a corrugated structure, which was first reported in the optical region [4] to assist the subwavelength aperture to achieve extraordinary transmission (ET) and a highly directive beam. Surface plasmon (SP) excitation has been well accepted to explain ET, while the beaming effect has been attributed to the coherent interference of energy emitted from the grooved region and the aperture [5–8]. Following this, a surface corrugated structure has been scaled into the microwave region, where ET and beaming phenomena have also been reported experimentally as well [9–12]. The corrugated structure is well known to antenna designers, it often being utilised as choke grooves to suppress surface wave diffraction at the grounded edge. However, the surface wave in our proposed corrugation is excited, modulated and then reradiated. Pendry *et al.* [13] adopted spoof SPs whose dispersion relation has strong similarities with that of SPs to describe this surface electromagnetic mode in the corrugated structure in the microwave region.

Recently, application of this corrugated structure has been intensively investigated [14–15]. In particular, its beaming property can be developed in the antenna field to improve radiation performance [3, 16–21]. So far, both straight grooves and concentric grooves have been employed in slot antenna arrays [3, 16–19] and patch antennas [20–21]. The loaded grooves in the above antennas are often considered as secondary radiation sources which lead to reradiation of surface EM energy [3, 17–21]. In this paper, taking advantage of its role of secondary radiation sources, a surface corrugated structure is utilised in a 2 × 2 slot array with element spacing larger than a wavelength in the *E* plane. Simulated radiation patterns show that employment of the corrugated structure can largely improve antenna gain by about 8 dB and sharply suppress high grating-lobe levels in a flat slot array without grooves. This antenna has been fabricated and measured, and good agreement is obtained between the measured and simulated results.

2 Antenna model and results

The corrugated 2 × 2 slot antenna array was fabricated with a numerical control machine, and its geometric model is presented in Fig. 1, which is similar to the two slot linear array proposed in [3]. The slot size is designed to be



a

b

c

Fig. 1 *2 × 2 slot antenna array using corrugated structure*
a Simulation model of the designed antenna
b Side view of the simulation model
c Fabricated antenna array

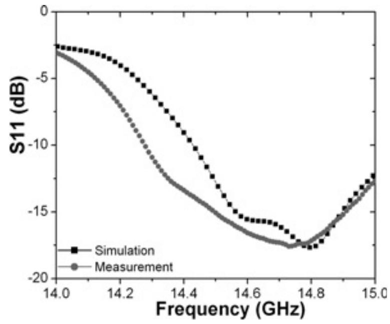
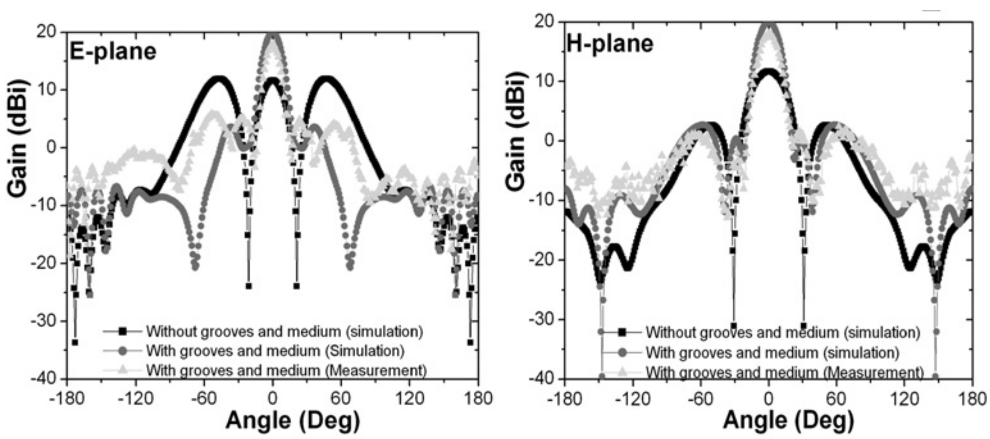


Fig. 2 *Reflection coefficient of the corrugated 2 × 2 slot antenna array*

10.35 mm × 1.5 mm to make this antenna work at 14.5 GHz. Two grooves are milled between slot elements for constructing the secondary radiation source and other grooves are placed at the edge of slot antenna array, as shown in Fig. 1*a*. In our antenna array, the groove depth and width determine the groove cavity mode, which are often initialised to be $d = 0.15\lambda$ (less than 0.25λ) and $w = 0.1\lambda$, while the ground thickness h is required to be just larger than the groove depth d and is often initialised to be $h > 0.25\lambda$. Owing to the introduction of a dielectric medium, the distance *P1* between grooves can be initialised to be 0.5λ for forming slot-dipole resonance as the secondary radiation source. The distance P between slot and groove affects the coupling between them, which is also initialised to be 0.5λ here. Finally, the groove parameters are optimised as follows: groove depth $d = 3.2$ mm, groove width $w = 2.5$ mm, distance between the slot and groove $P = 9$ mm and distance between grooves $P1 = 10.5$ mm. The actual distance between two slots is $dx = 28.5$ mm in the E plane, while it is $dy = 20$ mm in the H plane. The commercially available material Rogers TMM 10i with permittivity of $\epsilon_r = 9.8$ and a thickness of $t = 1.5$ mm is adopted as the dielectric layer loaded between neighbouring grooves. The waveguide feeding network is designed to make the energy equally coupled to two slot elements distributed along the x-axis. Hence, there are only two waveguides as the input ports of EM wave, as shown in Figs. 1*a* and *b*.

Numerical simulation was performed by using the commercial software CST Microwave Studio to analyse this antenna performance. In the simulation, two waveguide ports are defined at the ends of two waveguides of our antenna, respectively. One waveguide port is excited, working as an excitation source to perform calculation of S11. The other one is not excited, behaving as a matched load. In the experiment, one waveguide of our antenna is connected to one port of the vector network analyser and the other one is connected to the matched load. The reflection coefficient of this antenna is given in Fig. 2. The measured result agrees well with the simulated one. The designed antenna resonates well around 14.5 GHz and its bandwidth where the value of S11 is less than −10 dB is very broad. The antenna was then tested in an anechoic chamber. We introduced a two-way power divider here and made its two output ports connected to two waveguides of this antenna. The simulated and measured radiation patterns are shown in Fig. 3, which also includes the result for a flat slot array without grooves as comparison. It is seen that the gain of the flat slot array is only 11.9 dBi and its grating lobe in the E plane is so high, almost reaching the same level as the main lobe. After introducing a corrugated structure in the flat slot array, the antenna performance is largely ameliorated, and the simulated result agrees well



a

b

Fig. 3 *Comparison of radiation pattern of the 2 × 2 slot antenna array with and without grooves at f = 14.5 GHz*
a E plane
b H plane

with the measured results. The simulated gain is significantly increased to 19.93 dBi, while the measured gain is 2.05 dB less than the simulated one. The insertion loss of power divider and feeding power imbalance may be some of the reasons for the reduced gain. The half-power beamwidth (HPBW) in both *E* and *H* plane is greatly suppressed by 12° and 10°, respectively, indicating the enhancement of antenna directivity. It is noted in Fig. 3 that the high grating-lobe level in the flat slot array without grooves is sharply suppressed and its measured side lobe level (SLL) is −11.5 dB, about 5 dB higher than the simulated one. This discrepancy may result from the difference between dielectric property of the dielectric layer adopted in the experiment and simulation. The permittivity and the thickness excursion in the experiment would sharply degrade the antenna performance, which is well described in [3]. In addition, we still calculated the gain and SLL at a very broad frequency band, as seen in the Fig. 4. It is seen that the maximum gain is 19.93 dBi at 14.5 GHz and the antenna gain stays above 19 dBi from 14.4 Hz to 14.8 GHz. Hence the radiation bandwidth (defined as a frequency band where the variation of gain is less than 1 dB below the maximum value) is about 400 MHz, while the SLL can also remain low (meaning the SLL is less than −10 dB) for a similar bandwidth, which is from 14.4 to 15.0 GHz.

Fig. 5*a* shows the influence of the varying groove number on the antenna gain and HPBW in the *E* plane. The groove number *n* is the sum of the central grooves number and marginal grooves number. In the structure of the proposed slot array antenna, the number of central grooves is two and the marginal groove number is four, thus the sum of its groove number is six. We can tune this value by increasing or decreasing the marginal groove number. It is seen in Fig. 5*a* that the antenna gain is enhanced with the increase in groove number and then reaches a maximum value of 20.4 dBi for $n = 10$, where the HPBW in the *E* plane is also suppressed to the minimum value of 13.3°. It is well understood that the marginal grooves participate in the reradiation of the surface EM wave and then contribute the further improvement of the antenna performance. However, since the marginal groove region is far from the slot source and their excited surface EM strength is rather weak [17], the contribution of surface EM energy reradiated by the marginal grooves in the grounded edge can be neglected and the antenna gain reaches saturation, when the value of the groove number *n* exceeds ten. The variation of the antenna gain and SLL is investigated as a function of distance *dy* between slot elements in the *H* plane, and the related result is presented in Fig. 5*b*. It shows that the gain is slightly decreased from 20.2 to 19.1 dBi when the value of *dy* varies from 18 mm (0.87λ) to 30 mm (1.45λ) with a step of 2 mm. Meanwhile the corresponding SLL in the *H* plane is slightly increased and the values are less than −15 dB for all cases, which is beyond our expectation. The above result strongly suggests that the loaded surface grooves can also enlarge the element spacing in the *H* plane without obviously degrading the antenna performance. The reason for this interesting phenomenon is discussed in the next section.

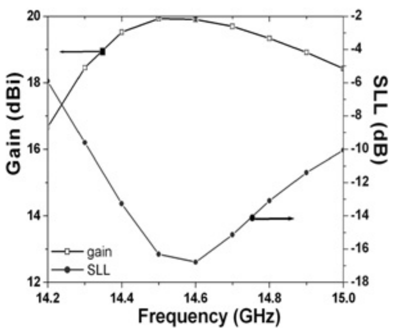


Fig. 4 *Simulated gain and SLL of the proposed antenna at a very broad frequency band*

3 Discussion

Fig. 6*a* shows tangential component of electric field distribution at surface of the 2 × 2 slot array with and without grooves. The surface electric field energy only exists in the slot region of the flat slot array, while in our designed antenna, the grooved regions 1, 2 and 3 also retain relatively high electric field strength, besides the similar energy distribution in the slot region. Since the tangential component of electric field contributes to the radiation performance in the far field, it may be expected that the corrugated slot array will radiate more energy to vacuum, compared with the flat slot array. This simulation model is

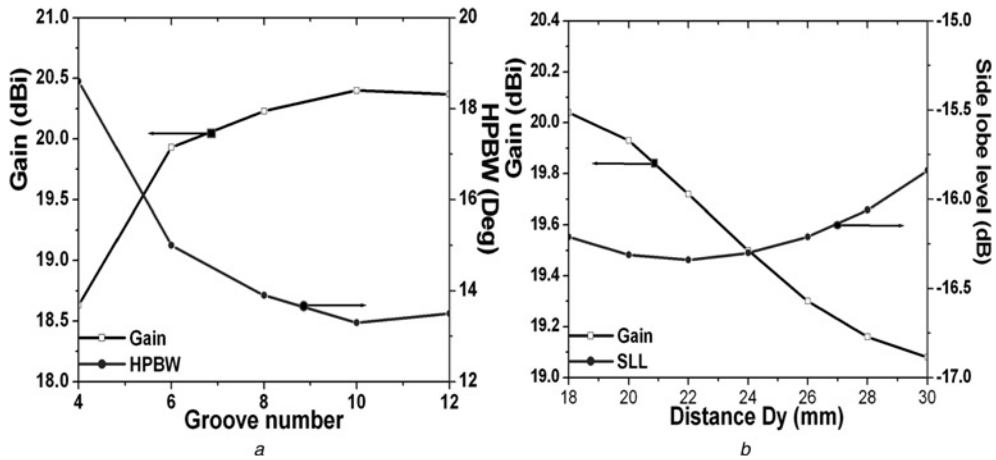


Fig. 5 *Response of antenna performance to different parameters*

a Antenna gain and HPBW in the *E* plane as a function of groove number
b Antenna gain and SLL in the *H* plane as a function of distance *dy*

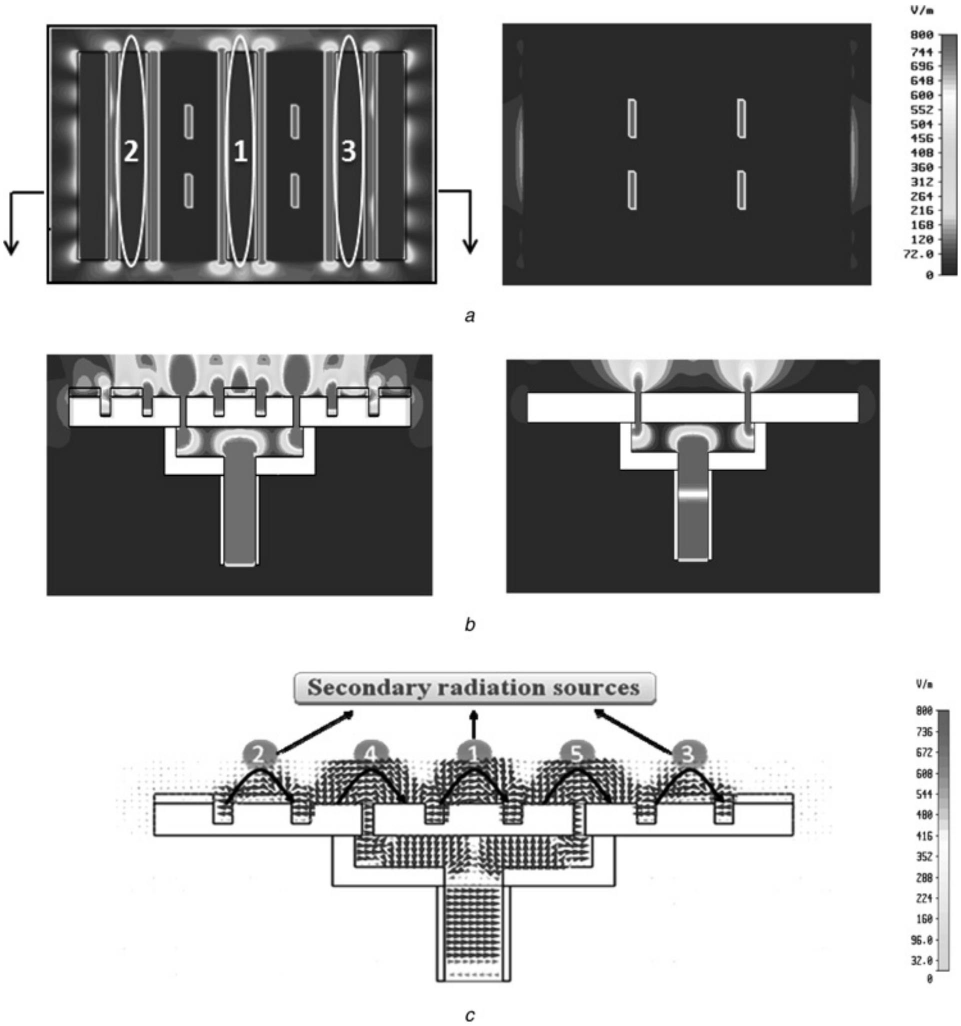


Fig. 6 *Electric field distribution of the antenna array with and without grooves at f = 14.5 GHz*

a Tangential component of electric field at antenna surface
b Tangential component of electric field in the *E* plane
c Complex amplitude of electric field in the *E* plane

then cut along the direction indicated by arrows in Fig. 6*a*, and the tangential component of electric field distribution in the *E* plane of the 2 × 2 slot array with and without grooves is compared, as shown in Fig. 6*b*. Strong radiation is seen in the grooved region 1, 2 and 3, which can be considered as secondary radiation sources. It is worthwhile to point out that introducing secondary radiation sources in the region 1 indirectly reduces the effective distance between slot elements to be within a wavelength. Fig. 6*c* plots the complex amplitude of the electric field distribution in the *E* plane of this corrugated slot array. The strong slot-dipole radiation mode is seen above the primary sources region 4 and 5, whereas the similar, relatively weak and in-phase radiation mode is also formed above the grooved regions 1, 2 and 3, which further demonstrates the role of the loaded corrugation, as secondary sources which reradiate surface electric field energy. Thus it can be concluded that the coherent superposition of the energy from two slot primary sources and three secondary sources composed of grooves constructs the radiation pattern of this antenna in the *E* plane, resulting in the enhancement of antenna directivity.

It is worth noting in Fig. 6*a* that loading the corrugated structure makes the tangential electric field energy more uniform along the groove length direction, and some energy is reradiated into free space, influencing the radiation pattern in the *H* plane. Analyse the electric field distribution in the *H* plane of the slot array, we cut the antenna array along the central plane of the whole structure and central plane of one slot element in the groove direction, as seen in the left and right sides of Fig. 7*a*, respectively. Fig. 7*b* shows the tangential component of the electric field distribution in the *H* plane of the corrugated slot array and Fig. 7*c* presents the corresponding case of the flat slot array for comparison. It is noticed that the distribution of electric field energy radiated from the slot sources region is almost the same between the slot array with and without grooves. However, there is some obvious difference between the electric field distributions above the grooved region (in the *YOZ* plane) for these two antenna structures. For the case of the corrugated slot array, high electric field strength is seen in the radiation space owing to the existence of the secondary radiation source, as shown in the left side of Fig. 7*b*. Note that this strong electric field radiation is not just localised to a small region like the single slot, and reversely originates from the entire central groove region. Hence this secondary radiation source can be equivalent to a linear H-plane slot array with unequal power ratio in feeding. For the

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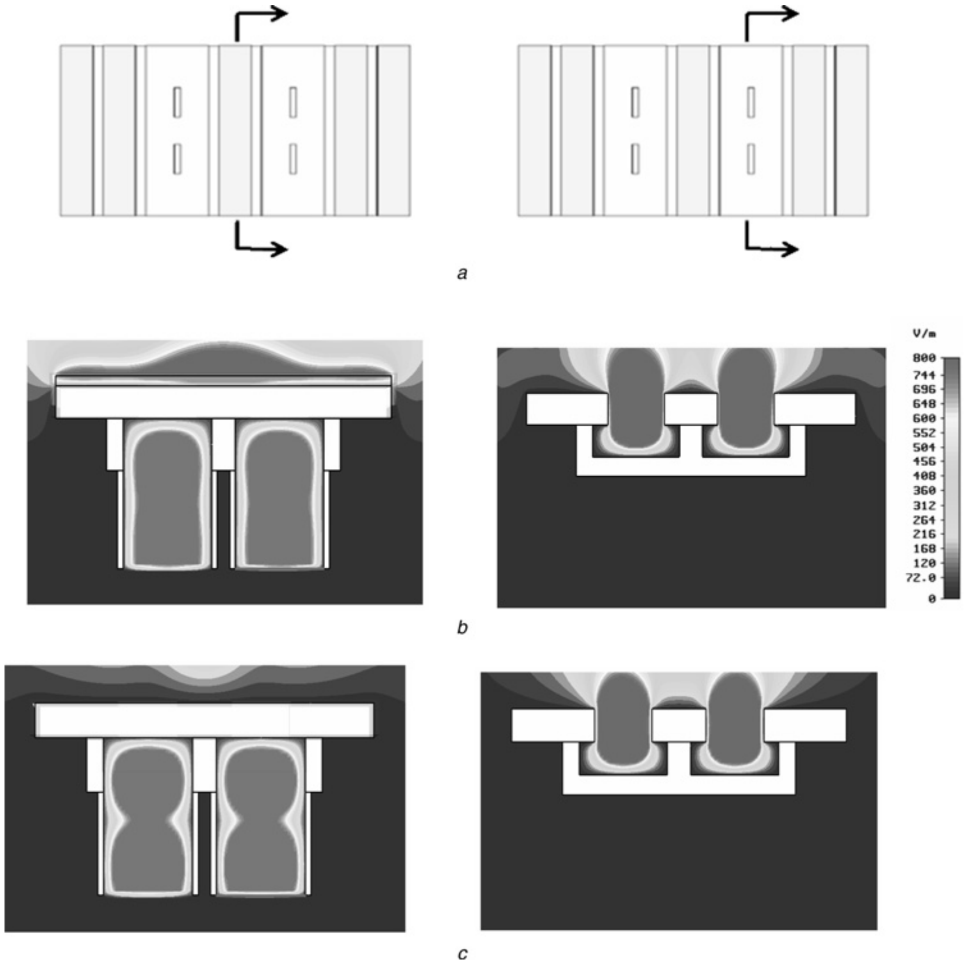

Fig. 7 *Comparison of electric field distribution in the H plane of the antenna array with and without grooves at f = 14.5 GHz*

a Location of cut in the simulation model
b Antenna with corrugated structure
c Antenna without corrugated structure

case of the flat slots array, there is almost no radiation above the same region, as seen in the left side of Fig. 7*c*. It is well known that the SLL is rapidly degraded in conventional antenna arrays, if the element spacing exceeds a wavelength. Nevertheless, the loaded secondary sources in our antenna make up the above influence and avoid appearance of the high grating lobe, although the value of *dy* is increased to beyond a wavelength.

4 Conclusion

In conclusion, secondary radiation sources are employed in a 2×2 slot array with large element spacing to ameliorate the antenna performance. This secondary source is composed of a corrugated structure, which can influence surface EM wave propagation and reradiate parts of the surface EM energy into free space. The measured results show that the antenna gain is increased to 17.9 dB and the high grating lobe in the *E* plane is sharply reduced. Moreover, it is found that the antenna gain and SLL in the *H* plane are not sensitive to the increase in distance between slot elements, indicating that the introduction of the secondary radiation sources can realise large element spacing in both *E* and *H* planes. This method of constructing secondary sources in the antenna array has broken the limitation of conventional elements distribution and also shown its superiority by just adopting a few elements to achieve high gain.

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