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Performance of Modified Silicon-Based Optical Leaky-Wave Antenna Structures

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ABSTRACT

Conventional silicon-based optical leaky-wave antennas (OLWAs) have been investigated in the literature as high directivity narrow-beam radiators with steering capability and designed for 1550 nm operation using single-grating layer. In this paper, two modifications are introduced to the conventional silicon-based OLWA. The first modification is to redesign the structure for 1300 nm operation and to compare the radiation parameters with those of the 1550 nm counterpart. The second modification is to design and investigate the performance of a double-grating OLWA which is useful for double-beam steering.

Indexing terms/Keywords

Optical leaky wave antenna (OLWA); Silicon-based antenna; Silicon optical antenna..

Academic Discipline And Sub-Disciplines

Electronics and Data Communications.

SUBJECT CLASSIFICATION

Optical antennas

TYPE (METHOD/APPROACH)

Simulation work.

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1. INTRODUCTION

Silicon-based photonics have generated nowadays a huge interest mainly for optical telecommunications and increasingly also for sensing The development of elementary passive and active components has reached such a performance level that the combination of these building blocks can lead to the development and the commercialization of high performance transceivers [1] This progress is mainly driven by the compactness of the integrated optical components and the fact that these devices can be fabricated using the mature complementary metal-oxide-semiconductor (CMOS) fabrication infrastructure, resulting in high yield and high volume fabrication [2]. In fact CMOS platform dominated the microelectronics industry in the last 40 over years through the enablement of complex low power electronic circuits with high yields. Silicon is a very good optical waveguide material for 1300 nm and 1550 nm wavelength regions (usually used in optical communications) because it is transparent beyond 1.1 µm and has high refractive index contrast (with SiO_2).

Recently, there is increasing interest to extend the concepts of microwave antennas to optical frequencies leading to optical antennas. These antennas have the ability to control the emission and scattering of light with a small-scale footprint [3-5]. For example, a novel silicon-based optical leaky-wave antenna (OLWA) has been proposed to provide very directive radiation at 1550 nm [6]. This wavelength has been used widely in optical communication systems since it corresponds to the minimum attenuation wavelength in standard single-mode silicon fibers. The structure is CMOS compatible and hence can be fabricated on silicon-on-insulator (SOI) platform which is suitable for both optoelectronic and photonic integration [7]. Further, the radiation parameters of the reported antenna can be controlled by introducing excess carriers in the silicon via electronic or optical injection [7,8]. The OLWA consists of SiO_2-Si_3N_4-SiO_2 waveguide with silicon perturbations positioned on the bottom side of the silicon nitride core as shown in Fig.1. The structure is capable of radiating one main beam from the bottom side.

The effect of structure parameters on the far-field radiation of the 1550 nm OLWA proposed in [6] has been reported in the literature. Various radiation parameters are tracked during this parametric study such as scattering coefficients, radiation and total efficiencies, directivity, gain, main lobe magnitude and direction, side lobe level, and angular width of the main beam. The parametric study covers also the number of silicon perturbations, perturbation width, grating period, and the perturbation thickness. In this paper, the silicon-based OLWA is redesigned for 1300 nm operation and its performance is evaluated and compared with that of conventional counterpart operating at 1550 nm. Further, the structure of the OLWA is modified to radiate two main beams simultaneously by inserting additional silicon perturbations on the top side of the core waveguide. The results are based mainly on simulations obtained using the commercial software CST (CST STUDIO SUITE 2013).

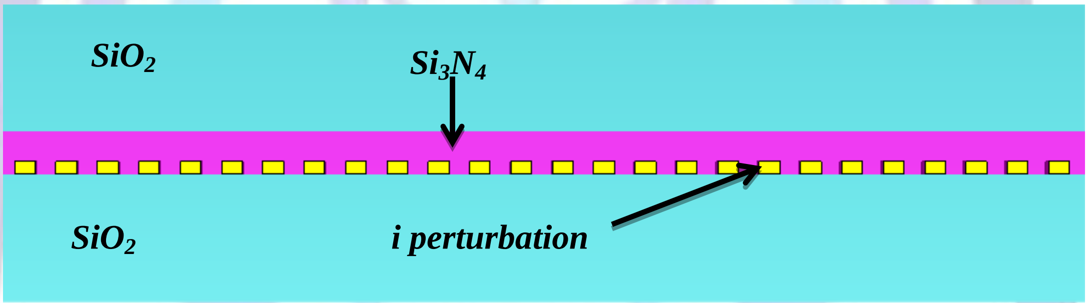


Fig. 1: Silicon-based optical leaky-wave antenna.

2. 1300 nm Optical Leaky-Wave Antenna

The structure under investigation is a single-grating antenna (SGA) similar to the structure shown in Fig. 1. The geometric parameters used in the design are waveguide thickness hw=1000 nm, thickness of the silicon bar h=300 nm, and the ratio of silicon bar width to perturbation grating period w/d=0.5. These values are similar to those adopted in the 1550 nm antenna design. However, the value of d depends strongly on the operating wavelength and should be chosen carefully.

At 1300 nm, the refractive indices of the materials used in the design are 3.5, 1.454, and 1.7 for Si, SiO_2, and Si_3N_4, respectively. Simulation results using CST yield an effective refractive index of 1.503. Using eqn. 1, the grating period d is estimated to be 830 nm to achieve $\theta_{shift}= -2.5^o$.

d

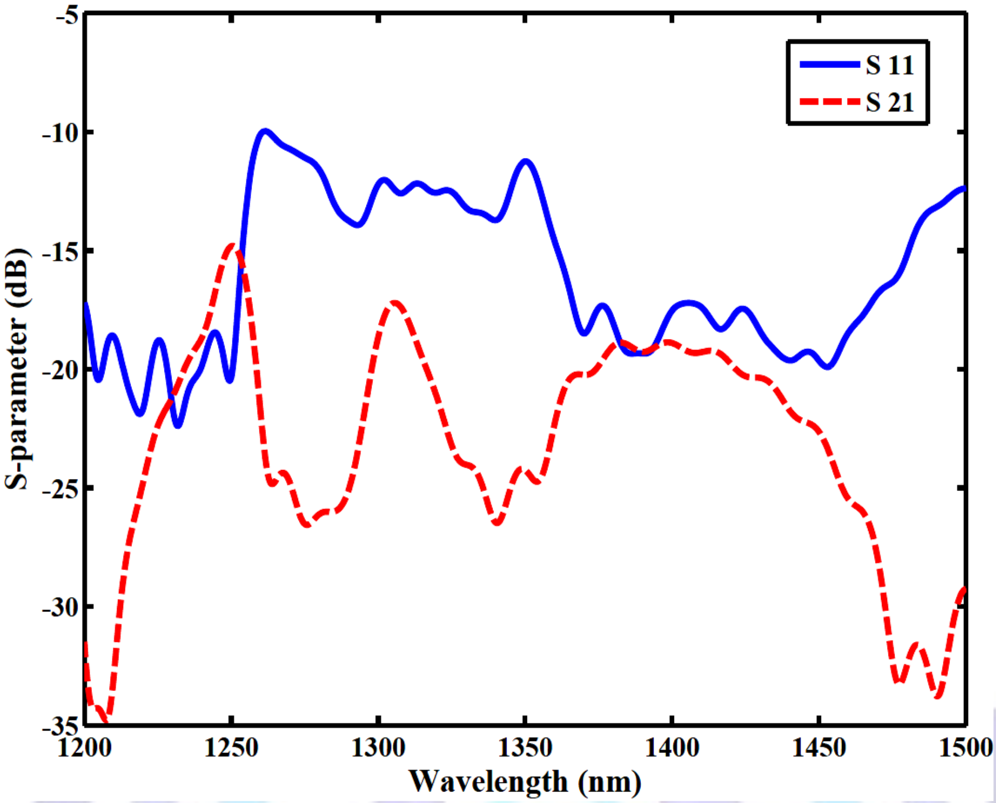
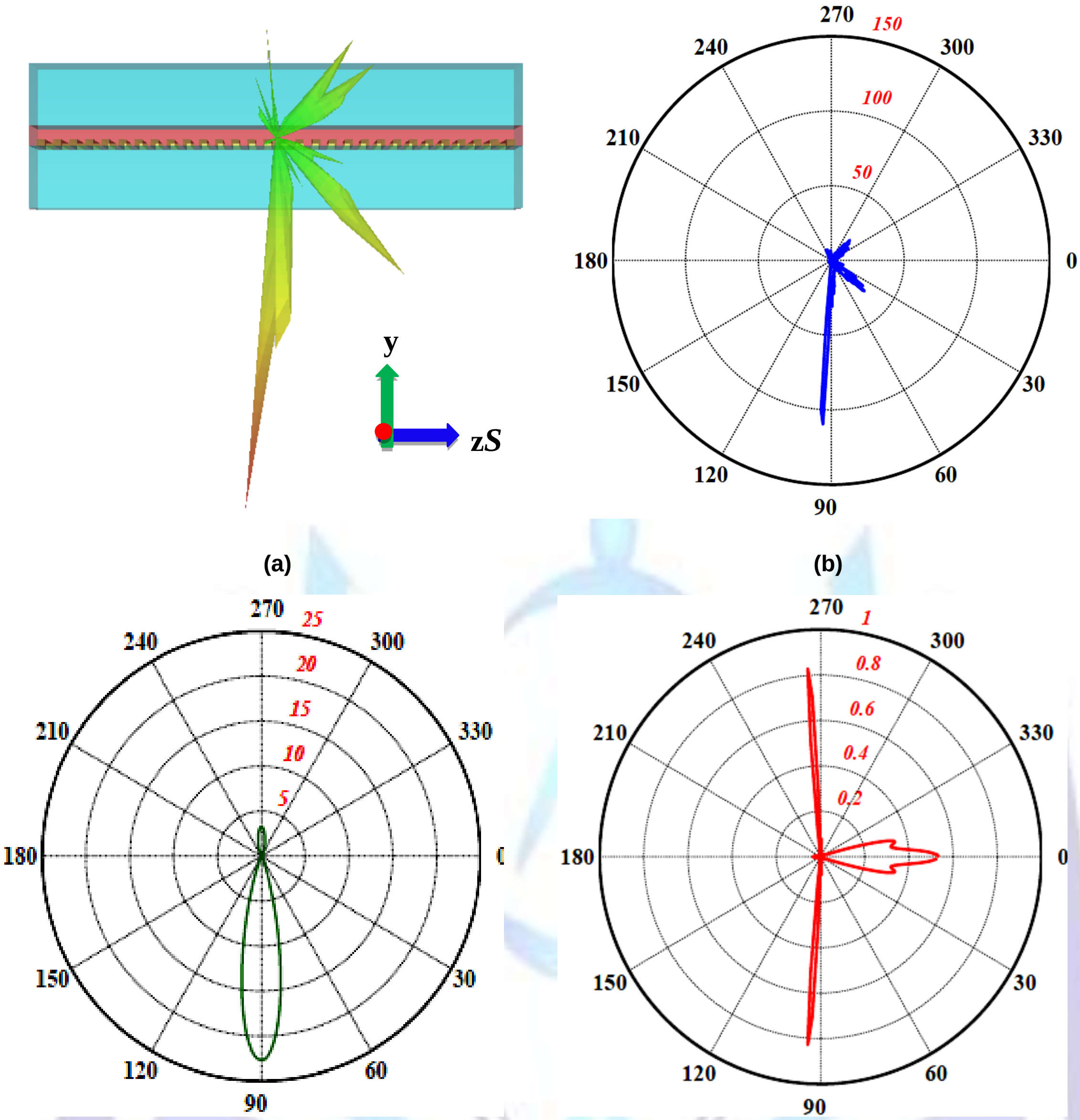


Fig. 2:Variation of scattering parameters S_{11} and S_{21} with wavelength for a 30 silicon-bar OLWA with grating period 830 nm.

(a) 3D farfield pattern (b) yz plane (c) xy plane (d) xz plane.

$$d = \frac{\lambda}{n_{eff} - n_b \cos\theta} \tag{1}$$

Figures 2 and 3 show the spectra of the scattering parameters S_{11} and S_{21} and the radiation patterns when the number of silicon perturbations N equals 30, respectively, note that S_{11} and $S_{21}$are less than -12 dB and -17 dB, respectively, for the 1300 nm wavelength. Results related to the 1550 nm LWA are listed in table 1 for comparison purposes. The values indicate clearly that the reflected and transmitted powers are almost negligible with radiated power. The direction of the main beam is 93^o which is in accord with the designed value (θ_{shift}= -2.5^o, i.e., main beam direction is 92.5^o). Table 1 summarizes the main radiation parameters values at 1300 nm compared to these at 1550 nm.



(a) (b)

(c) (d)

Fig. 3: Far-field characteristics of an OLWA operating at 1300 nm.

Radiation parameter	Value	
	1300 nm antenna	1550 nm antenna
S_{11} (dB)	-12.24	-14.27
S_{21} (dB)	-17.28	-18.29
Radiation efficiency	0.73	0.87
Total efficiency	0.68	0.82
Directivity (dB)	16.25	19.77
Gain (dB)	11.88	39.36
Main lobe magnitude (dB)	20.41	22.77
Main lobe direction (degree)	93.00	93.00
Side lobe level (dB)	-5.50	-9.30
3 dB angular width (degree)	2.60	3.00

Table.1 Comparison of the values of radiation parameters between two OLWAs operating at wavelengths 1300 and 1550 nm with N=30.

Investing the results in Table 1 highlights the following finding. The 1300 nm antenna has lower gain and efficiency compared with 1550 nm counterpart. The relatively lower efficiency result is attributed mainly to the higher losses of the waveguide at1300 nm as explained in the following.

The power incident on the antenna P_{in} is splitted into reflected power at the input facet P_r, power transmitted from the output facet P_t, power absorbed by the waveguide P_{loss}, and radiated power P_{rad}.

$$P_{in} = P_r + P_t + P_{rad} + P_{loss}$$

$$1 = \frac{P_r}{P_{in}} + \frac{P_t}{P_{in}} + \frac{P_{rad}}{P_{in}} + \frac{P_{loss}}{P_{in}}$$

Recall that $P_r/P_{in} = S_{11}^2$, $P_t/P_{in} = S_{21}^2$, and $P_{rad}/P_{in} = \eta_{tot}$, then

$$P_{loss}/P_{in} = 1 - (S_{11}^2 + S_{21}^2 + \eta_{tot}) \tag{2}$$

The radiation efficiency is calculated from

$$\eta_{rad} = \frac{P_{rad}}{P_{rad} + P_{loss}} = \frac{P_{rad}/P_{in}}{P_{rad}/P_{in} + P_{loss}/P_{in}} = \frac{\eta_{tot}}{\eta_{tot} + P_{loss}/P_{in}}$$

Therefore

$$P_{loss}/P_{in} = \frac{\eta_{tot}}{\eta_{rad}} - \eta_{tot} \tag{3}$$

For the 1300 nm antenna, S_{11}= -12.24 dB, S_{21}= -17.28 dB, $\eta_{rad=}$ 0.73, and η_{tot} = 0.68. Therefore, P_r/P_{in} = 0.06, P_t/P_{in} = 0.0187, and P_{loss}/P_{in} = 0.241 (from eqn. 2) or 0.251 (from eqn. 3). Similar calculations are performed for the 1550 nm antenna which yield P_r/P_{in} = 0.0374, P_t/P_{in} = 0.0148, P_{loss}/P_{in} = 0.128 (from eqn.. 2), and 0.123 (from eqn. 3). These results indicate clearly that the 1300 nm antenna has higher losses than the 1550 nm antenna (approximately twice) leading to lower total and radiation efficiencies.

Table.1 Comparison of the values of radiation parameters between two OLWAs operating at wavelengths 1300 and 1550 nm with N=30.

Radiation parameter	Value	
	1300 nm antenna	1550 nm antenna
S_{11} (dB)	-12.24	-14.27
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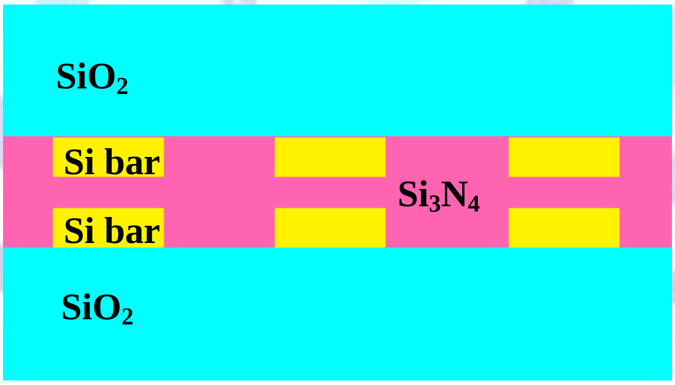
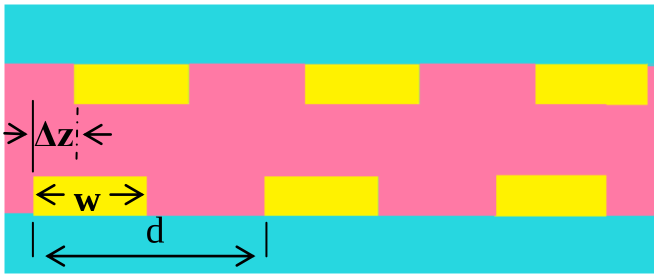
3- Double-Grating Optical Leaky-Wave Antenna

This section proposes new silicon-based LWA having two silicon perturbations layers (gratings) inserted in the Si_3N_4 waveguide core. The effective core is bounded by the two gratings as shown in Fig. 4. The Si perturbation width w and grating period d are identical for both gratings and chosen to support the required operating wavelength. This leaves two parameters that can be used to tune the radiation characteristics of the two radiation beams. The first parameter is the thickness of the upper grating or/and lower grating while the other parameter is the axial shift between the two gratings (see Fig. 3b). The normalized axial shift (NAS) is defined as $\Delta z/w$ where Δz represents the axial offset between the two gratings. Therefore, $w-\Delta z$ represents the axial overlapping between the upper and lower silicon perturbation elements. For NAS=0, the upper grating is axially identical to the lower grating. (i.e., the two gratings are in phase). For NAS=100%, the two gratings are out of phase.



(a)



(b)

Fig. 4: (a) Schematic diagram of a double-grating leaky-wave antenna.
(b) Definition of the normalized axial shift parameter.

The simulation results presented in this section are for 1550 nm double-grating antenna (DGA) designed with 30 silicon perturbations per grating (i.e., N=30). Unless otherwise stated, the parameters values are h_w=1000 nm, d=967.5 nm, w/d=0.5, and h=300 nm (for both gratings).

3.1 Performance of DGA Designed with NAS=0

This structure can be considered as a conventional double-grating LWA introduced to yield two radiated main beams having identical radiation parameters. Figure 5 shows the spectra of the scattering parameters S_{11} and S_{21} when the antenna is designed with N=30. The related radiation patterns are displayed in Fig. 6. The main radiation parameters evaluated at 1550 nm are listed in Table 2. Results corresponding to a single-grating counterpart are also included in this table for comparison purposes. Investing these results highlights the following facts

(i) The DGA radiates two main beams having identical radiation characteristics. The direction angels of the main beams are $122^o$and 238^o.

(ii) The 2D radiation patterns in different planes can be spitted into two identical (symmetric) radiation patterns.

(iii) The radiation characteristics of the DGA is not the superposition (i.e., linear contribution) of two isolated SGAs. In fact the coupling between the two gratings cannot be neglected since the distance between them (400 nm) is the operating wavelength (1550 nm).

(iv) The DGA has higher reflection coefficient (i.e., S_{11}) at the input (feeding) fact of the waveguide compared to the SGA. This result is attributed to the increase of refractive index of the core region since two silicon perturbations are inserted in transversal direction (normal to the direction of propagation).

(v) The DGA has slightly higher radiation efficiency and lower total efficiency compared with SGA.

(vi) The gain of the DGA is less by 27.7 dB compared with the gain of the SGA.

Note that the DGA has S_{11}=- 7.55 dB, S_{21}= -27.30 dB, η_{tot}= 0.75 at 1550 nm. These values yield P_r/P_{in} = 0.1758, P_t/P_{in} = 0.0019, and P_{loss} /P_{in} = 0.0723 (from eqn. 5.2). Note also that the DGA is characterized by higherP_r/P_{in} and lower P_{loss} /P_{in} compared with the SGA. These results lead to higher radiation efficiency and lower total efficiency for the DGA according to eqn.s. 1 and 2.

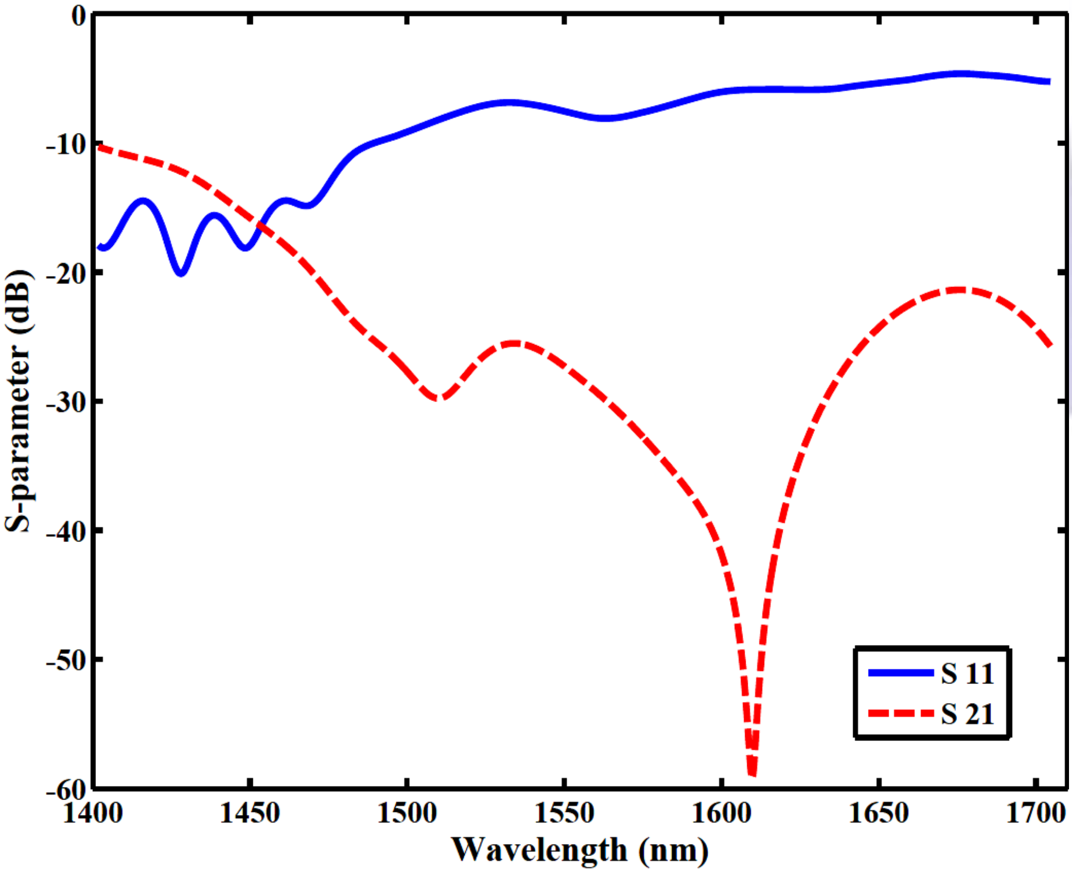
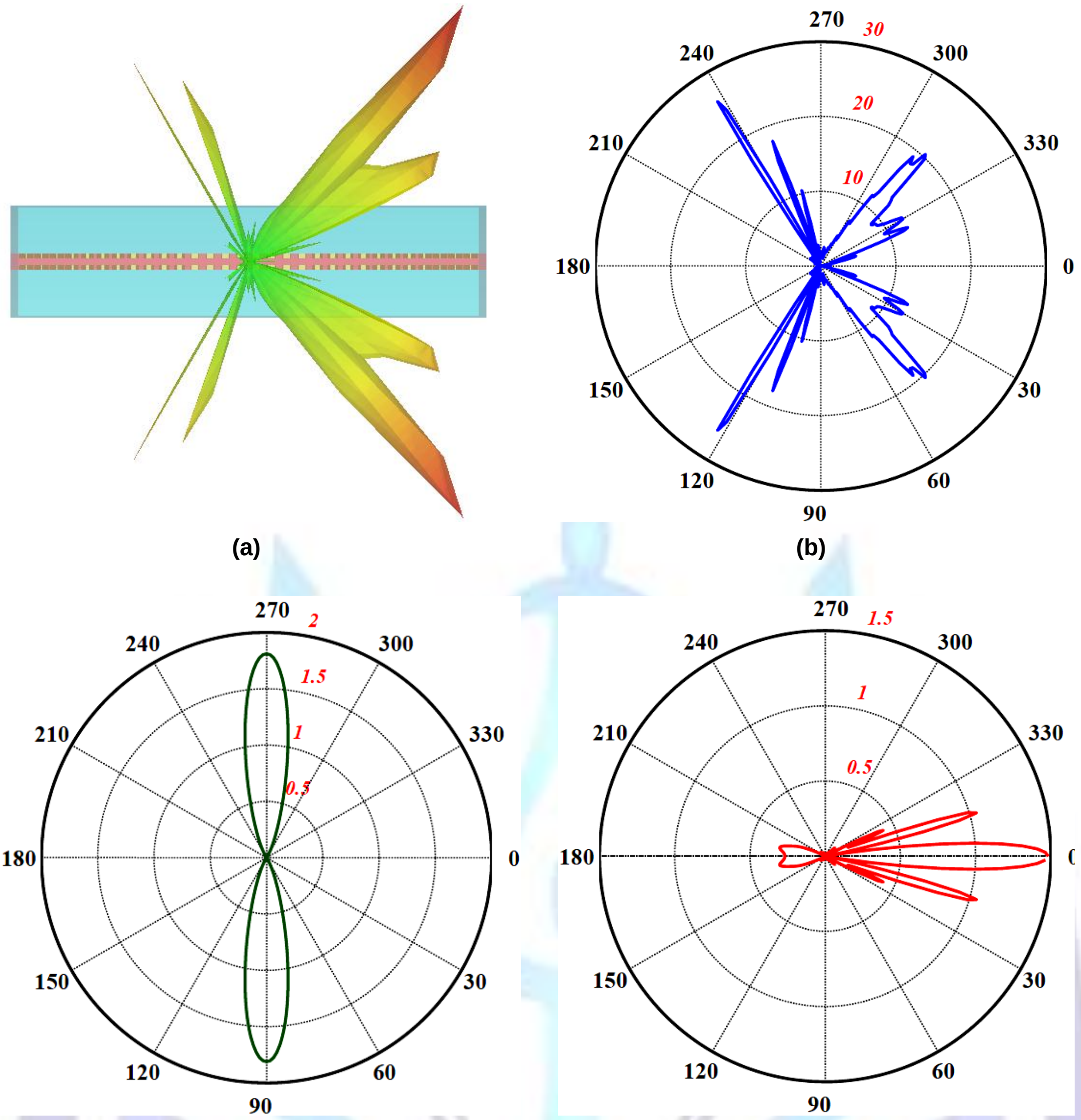


Fig. 5: Variation of scattering parameters S_{11} and S_{21} with wavelength for a 30-silicon bar OLWA designed with double grating.



(a) (b)

(c) (d)

Fig. 6: Farfield characteristics of a double-grating OLWA designed with N= 30 and operating at 1550 nm.

(a) 3D farfield pattern (b) yz plane (c) xy plane (d) xz plane.

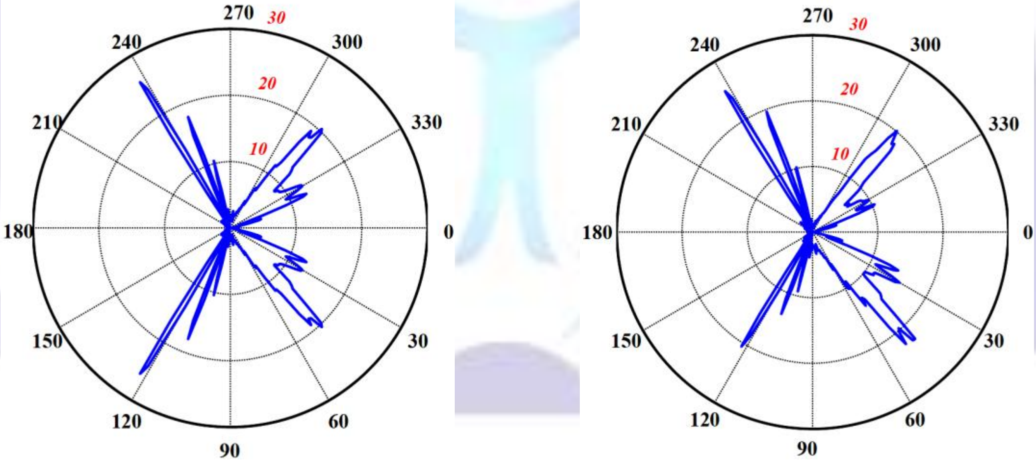
Table 2 Comparison between radiation parameters of DGA and SGA designed with N=30 and operating at 1550 nm.

Radiation parameter	Value	
	DGA	SGA
S11 (dB)	-7.55	-14.27
S21 (dB)	-27.30	-18.29
Radiation efficiency	0.91	0.87
Total efficiency	0.75	0.82
Directivity (dB)	12.82	19.77
Gain (dB)	11.66	39.36
Main lobe magnitude (dB)	14.13	22.77
Main lobe direction (degree)	122.00, 238.00	93.00
Side lobe level (dB)	-1.00	-9.30
3 dB angular width (degree)	3.30	3.00

3.2 Effect of Axial Shift Between the Upper and Lower Grating

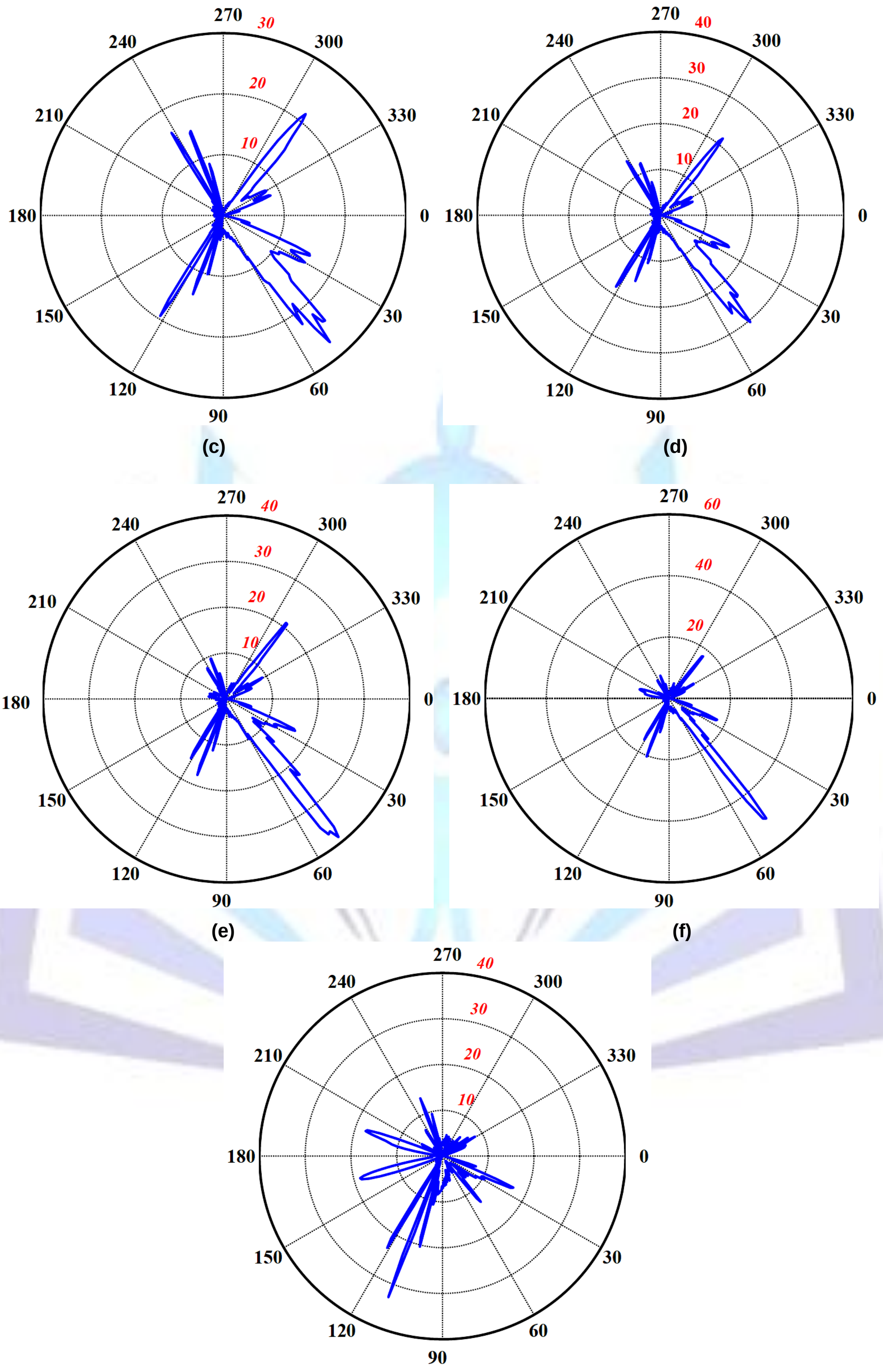
The aim of this subsection is to address the effect of the axial shift between the two gratings on the radiation parameters of the DGA. The simulation results are presented here when the antenna is operated at 1550 nm.

Figure 7 displays the radiation patterns for different values of NAS. The case of NAS zero corresponds to the conventional DGA investigated in Section 3.1. The variation of the radiation parameters evaluated at 1550 nm with the axial shift plotted in Fig. 8.



(a) (b)

Fig. 7:Radiation patterns of a double-grating LWA designed with different values of NAS. The results are reported for N=30 and λ=1550 nm. (a) 0 (b) 0.2 (c) 0.4(d) 0.5 (e) 0.65 (f) 0.8 (g) 1.

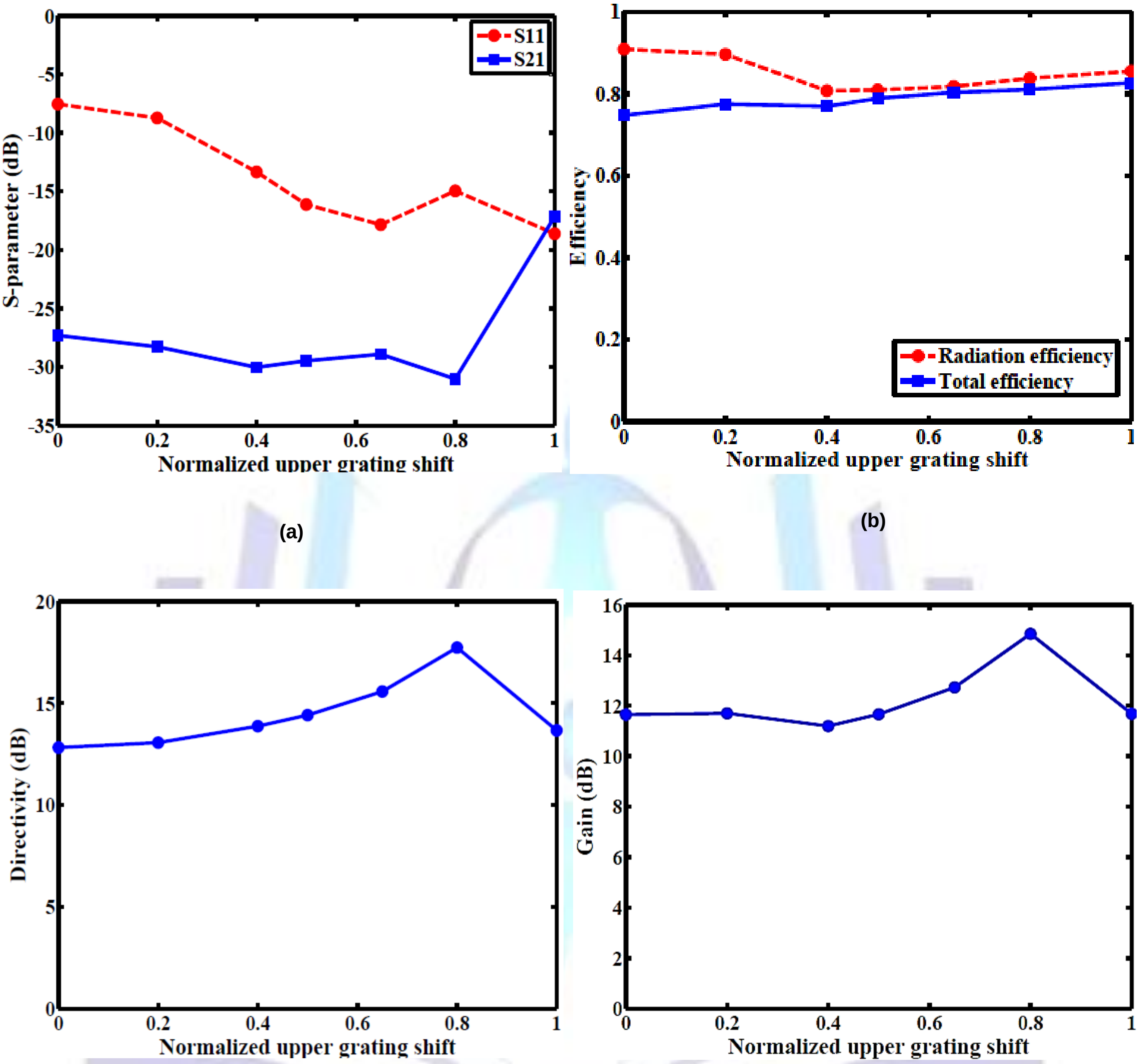


(c) (d)

(e) (f)

(g)

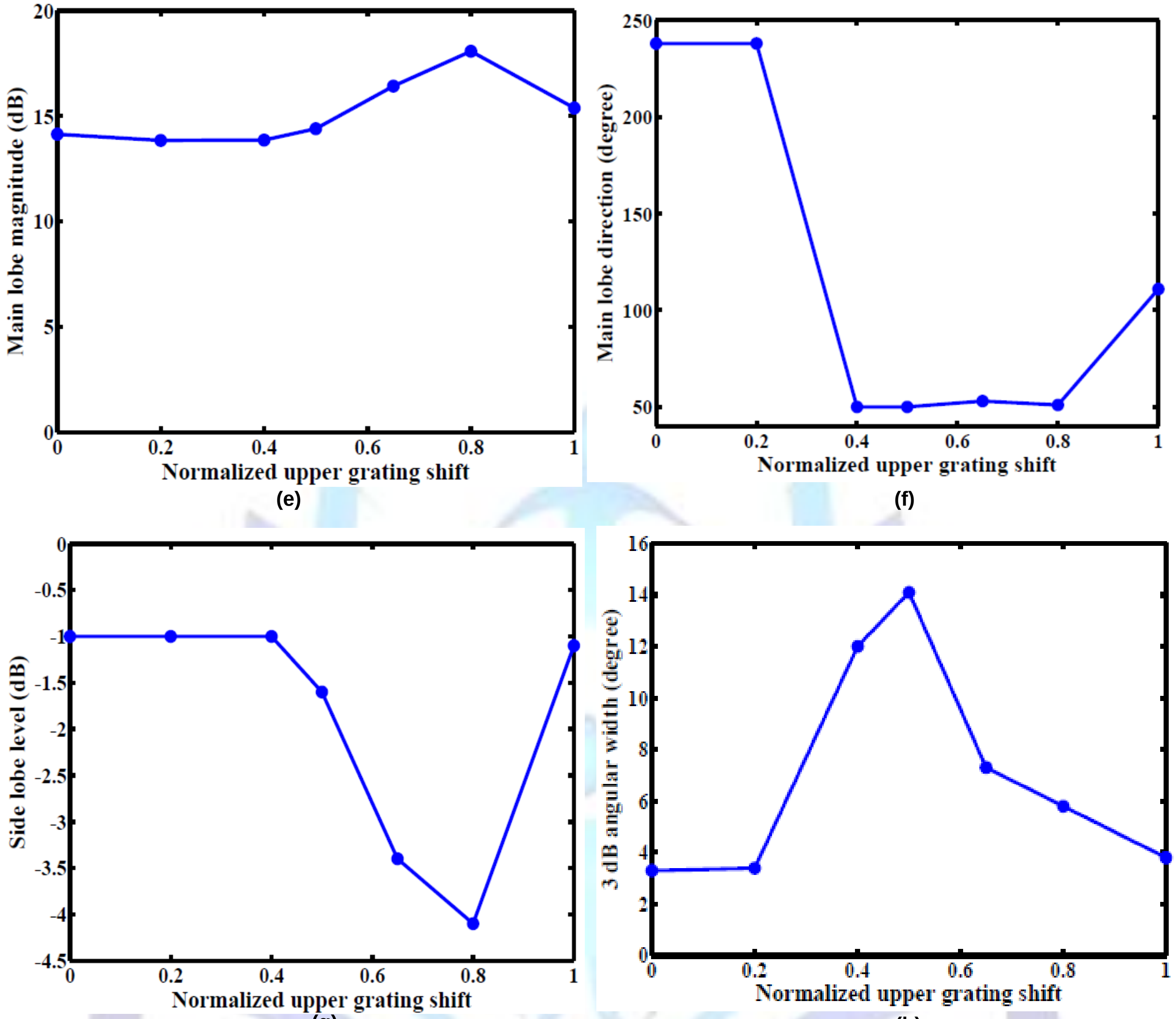
Fig. 7: (Continued).



(a) (b)

(c) (d)

Fig. 8: Dependence of radiation parameters of a double-grating LWA on axial shift when N=30 and λ=1550 nm.
(a) S-parameters (b) efficiency (c) directivity (d) gain (e) main lobe magnitude (f) main lobe direction (g) side lobe level (h) 3 dB angular width.



(e) (f)

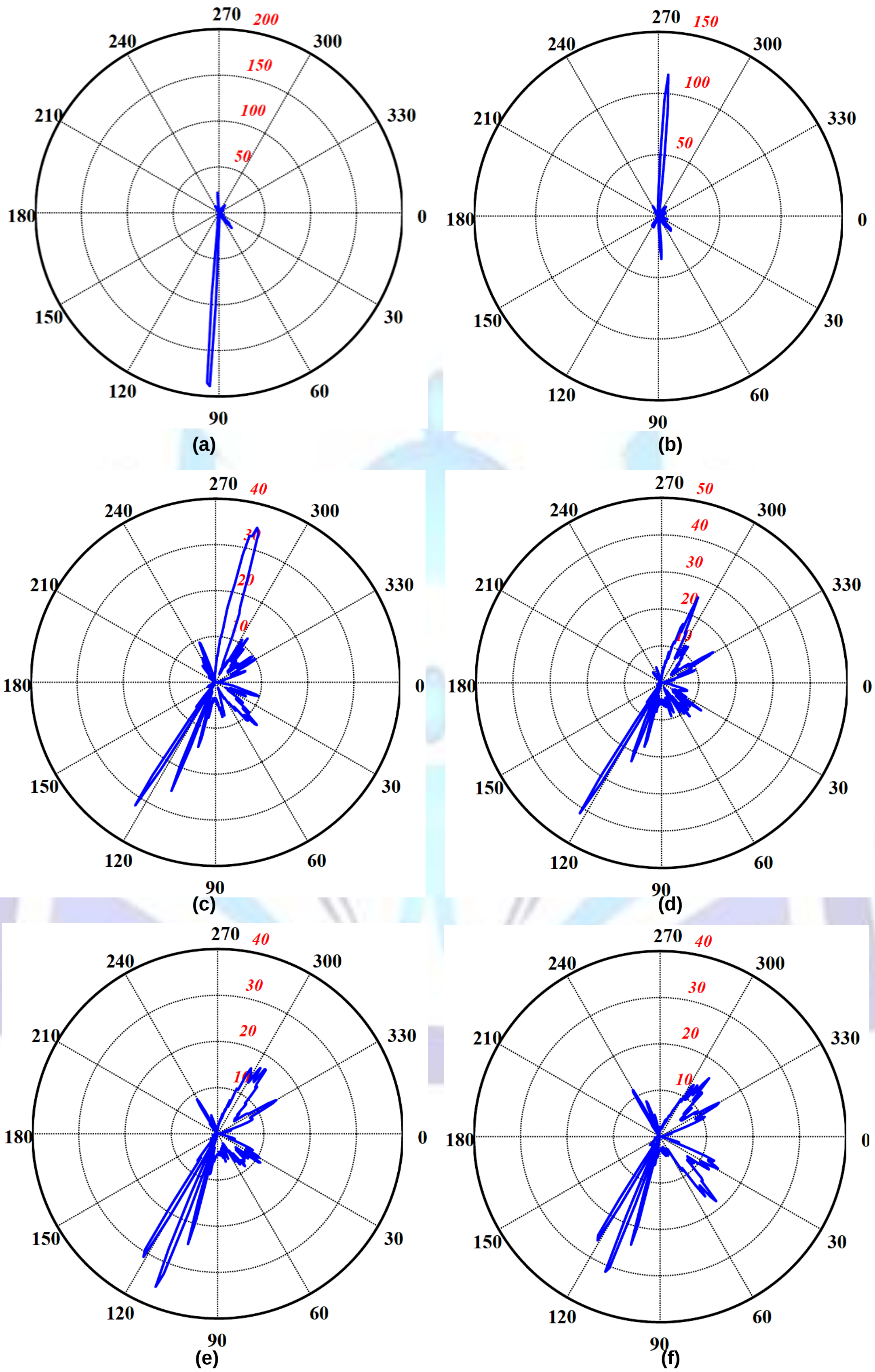
(g) (h)

Fig. 8: (Continued).

3.3 Effect of Upper Grating Thickness

The radiation parameters of the DGA can be tuned by varying the thickness of the upper grating h_u. This point will be presented in this subsection by addressing the dependence of antenna characteristics on $h_u$while keeping the thickness of the lower grating fixed at 300 nm. The NAS is set to zero in the following simulation. The case of h_u=0 corresponds to a single-grating LWA while the case of h_u=300 nm corresponds to the conventional double-grating LWA. The values of the radiation pattern are estimated at 1550 nm.

Figure 9 shows how the radiation pattern is affected by varying the thickness of the upper grating. Figure 10 shows the dependence of radiation parameters on the thickness of the upper grating. Note that the main beam direction varies over a wide range with the variation of the upper grating thickness.

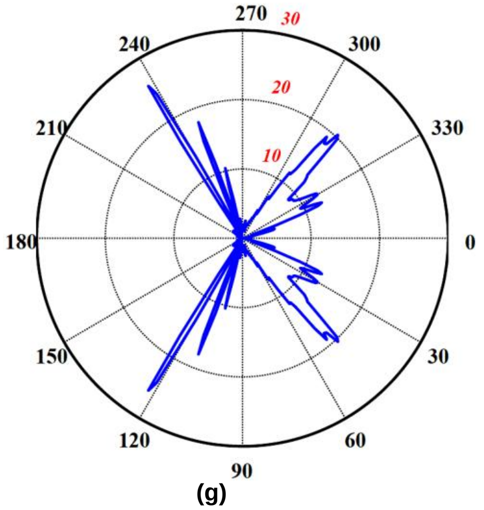


(a) (b)

(c) (d)

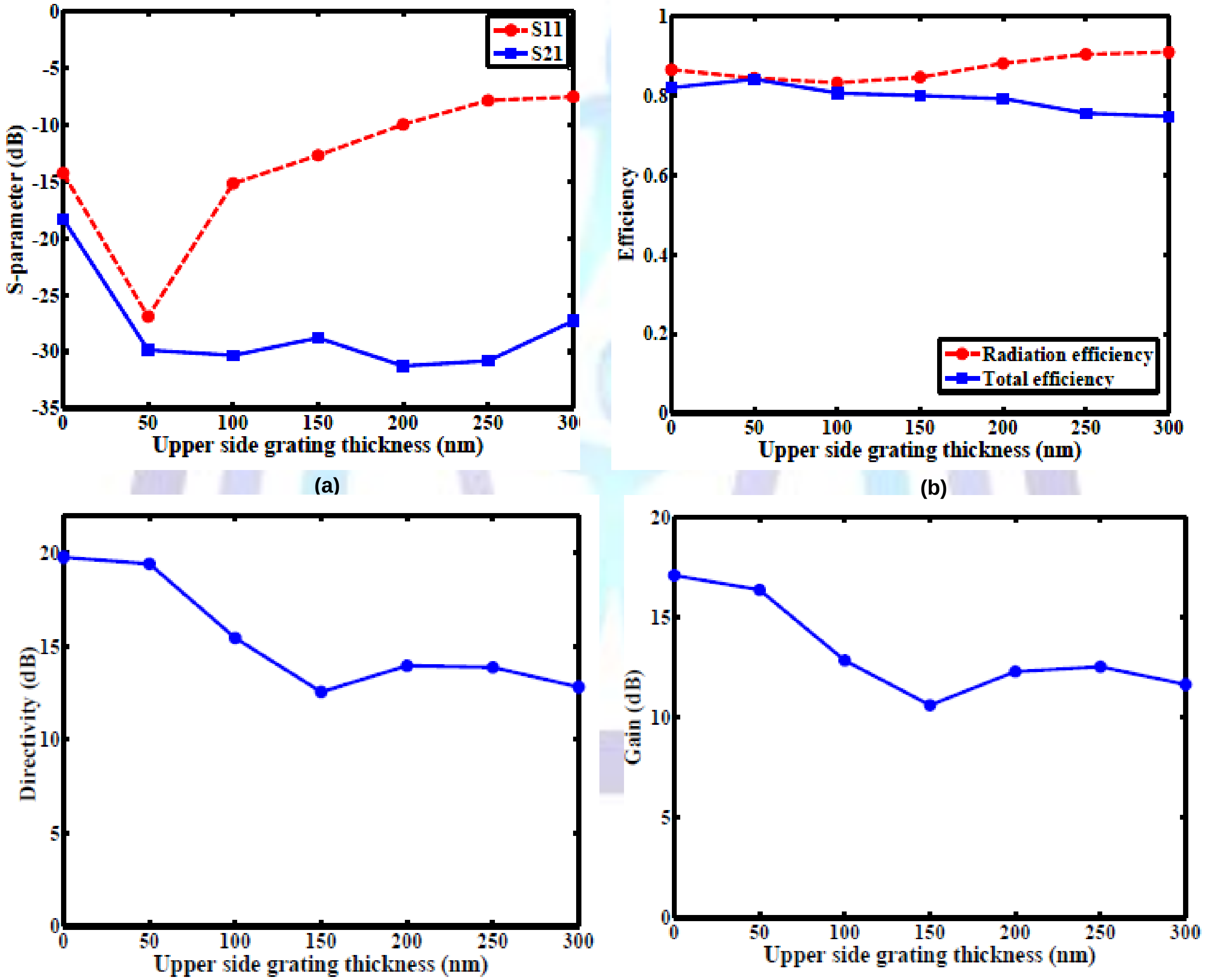
(e) (f)

Fig. 9:Radiation patterns of DGA designed different values of upper grating thickness. (a) 0 nm (b) 50 nm (c) 100 nm (d) 150 nm (e) 200 nm



(g)

Fig. 9:(Continued).



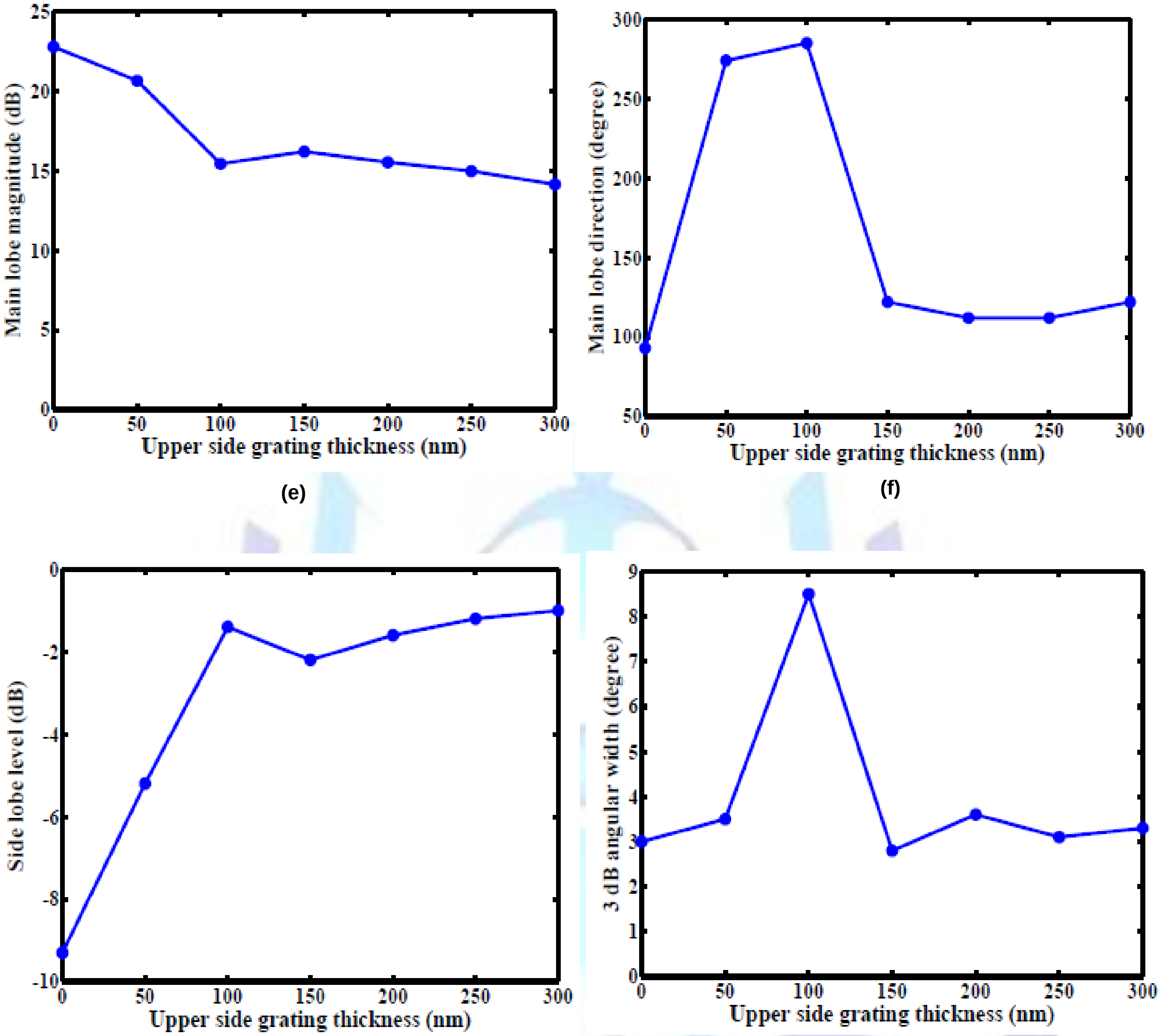
(a)

(b)

(c)

(d)

Fig. 10: variation of radiation parameters of a double-grating LWA with upper grating thickness when N=30 and λ=1550 nm. (a) S-parameters (b) efficiency (c) directivity (d) gain (e) main lobe magnitude (f) main lobe direction (g) side lobe level (h) 3 dB angular width.



(e)

(f)

(g)

(h)

Fig. 10: (Continued).

4. CONCLUSIONS

The performance of optical leaky-wave antenna (OLWA) designed using CMOS-compatible silicon platform has been investigated for 1300 nm operation. Parametric study has been performed to address the effect of geometric parameters on the radiation characteristics of 1550 nm double-grating antenna (DGA). The simulation results reveal that the 1300 nm antenna has lower gain and efficiency compared with 1550 nm counterpart. The relatively lower efficiency result is attributed mainly to the higher input interface reflection and waveguide losses at1300 nm. Further, the radiation characteristics of the DGA is not the superposition (i.e., linear contribution) of two isolated single-grating antenna (SGA) since the coupling between the two gratings) cannot be neglected since the distance between them (400 nm) is smaller than the operating wavelength (1550 nm).

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