A High Gain Slot Antenna Based on Surface Plasmon Polaritons

Hongjuan Han, **Huiping Guo**, **Xueguan Liu**, **and Ying Wang**
School of Electronic Information Engineering, Soochow University, Suzhou, China

Abstract— Surface Plasmon Polaritons (SPPs) have been attracting the interest of microwave technology researchers recently because of the the property of near-field enhancement. In this paper, firstly, we discuss the existence of SPPs in the surface of metal in microwave regime. We also analysis the motivation of SPPs. Secondly, we introduce a high gain slot antenna with single-layer director briefly. Thirdly, a four-layered slot antenna with compact size and high gain is proposed. This antenna is based on the previous antenna. The difference between them is that a dielectric grid structure is added to the last one. The dielectric grid structure makes the incident electromagnetic wave scattered, which makes the wave vector of the incident electromagnetic matched with the surface plasmon polaritons in horizontal direction, so that the incident electromagnetic wave can couple with SPPs. The simulated gain of the previous antenna is 12.0 dBi at 5.6 GHz and measured gain is 10.4 dBi at 5.57 GHz. The simulated gain of the last antenna is 13.5 dBi at 5.6 GHz and measured gain is 11.4 dBi at 5.57 GHz. The 2 dBi dropped for the measured and simulated gain can be caused by the loss of dielectric. By motivating SPPs, the simulated and measured gain of the antenna enhances nearly 1.5 dBi and 1 dBi separately. The overall size of both the antenna is $100 \times 100 \times 19\,\text{mm}^3$.

1. INTRODUCTION

Antennas for wireless communications are required to exhibit characteristics such as high gain, compact size, high efficiency, low cost, wide bandwidth and so on. In the design processing, many methods can be used to improve the antenna gain. Among them, the typical high gain antenna is the traditional Yagi antenna and novel microstrip Yagi antenna. However, in order to realize a gain of 12 dBi, 10 directors are required in [1]. Several microstrip-Yagi or quasi-Yagi antenna structures have been reported in [2–5], which have high gain and high front-to-back (F/B) ratio. However, these antennas have narrow bandwidth and large size. Recently, the multilayer-stacked Yagi antenna is becoming hot research in the miniaturization and high gain antenna. A multilayer-stacked microstrip Yagi antenna is presented in [6], High gain of 11 dBi and 10.28 dBi can be achieved respectively with adopted four layers of directors for dipole and dual polarization applications. Obviously there is an increased demand of antennas with compact size, broad bandwidth and high gain. In this paper, firstly, a miniaturized high gain slot antenna with single-layer director is presented, which has the properties of wide bandwidth, high gain and compact size. Secondly, referred to the first one, a novel high gain slot antenna based on the SPPs theories and features is proposed.

The proposed antennas are designed at 5.6 GHz and detailed discussion is given in the following sections.

2. THE THEORY OF SPPS

The surface plasmon polaritons (SPPs) are transverse magnetic surface waves propagating along the interface between two materials whose dielectric constants are opposite, generally a metal and dielectric [7]. SPPs are attenuating exponentially in the direction perpendicular to the surface. This is the electromagnetic mode of SPPs. The dispersion relation can be obtained by Maxwell's Equation and boundary condition [8].

$$E = E_0^{\pm} \exp\left(i\left(k_x x \pm k_z z - wt\right)\right) \tag{1}$$

with "+" for $z > 0$, "−" for $z \leq 0$ and with imaginary k_z which causes the field E_z damping exponentially. Suppose electromagnetic wave has wave number k and it is incident to an interface between dielectric (permittivity ε_1) and metal (permittivity ε_2). The wave number k is

$$k = 2\pi/\lambda \tag{2}$$

where λ is the wavelength of electromagnetic wave. According to Maxwell's Equation and the boundary condition at the surface, the normal component of the wave vectors satisfy the following relations,

$$\frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0 \tag{3}$$

$$\varepsilon_i \left(\frac{\omega}{c}\right)^2 = k_x^2 + k_{zi}^2 \quad i = 1, 2 \tag{4}$$

The wave vector k_x of surface plasmon is continuous through the interface. The dispersion relation can be written as

$$k_x = k_{spp} = \frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} = k_0\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \tag{5}$$

In the microwave regime, the permittivity of metal $\varepsilon_2 < 0$, $|\varepsilon_2| \gg 1$, $|\varepsilon_1 + \varepsilon_2| < |\varepsilon_2|$, thus, $k_{spp} > k_0$. Because of $k_{spp} > k_0$, the wave vector of the electromagnetic is not matched with the surface plasmons in horizontal direction, so that SPPs can't be excited. To excite surface plasmons, the wave vector of the electromagnetic must be matched with the surface plasmons in horizontal direction. In the visible and infrared frequency ranges, the typical method of realizing the coupling is using the diffraction of the metal or dielectric grid structures [9]. Comparing metal grid structures with dielectric grid structures, it is found that dielectric grid structures have better performance in enhancing the electromagnetic field and is more readily produced for industrial applications [10, 11].

In the microwave regime, SPPs do not exist in smooth metal surface. However, when there are periodic slits on the conductor, its Permittivity function is identified with SPPs in form by the equivalent medium processing [12].

3. PROPOSED SLOT ANTENNA WITH SINGLE LAYER DIRECTOR

The preliminary structure of the slot antenna with single-layer director as shown in Fig. 1 and Fig. 2, is named design 1, which contains a radiated slot on the metal plane called driver, a ground called reflector and a slot array in a metal plane called director. As noted in [6], three to four layers of directors are required to achieve high gain. Only one director layer is required to achieve a gain as high as shown in [6]. Dimensions of this structure are given in Table 1. The driver is designed on a 1.5 mm-thick FR4 substrate with dielectric constant (ε_{r1}) of 4.4 and the director is designed on the substrate with ε_{r2} of 2.55 and loss tangent of $\delta = 0.001$. The optimized distance between two slots is 13.75 mm, which is close to $\lambda/4$. The size of the director layer is $60(L) \times 60(L)\,\text{mm}^2$ and the distance from the director to the driver is D_2. All the parameters are listed in Table 1, where $D_1 = 11.5$ mm (0.205λ), $D_2 = 6$ mm (0.121λ), $L_2 = 38$ mm (0.709λ), $L_3 = 55$ mm (1.026λ) and $L_4 = 13.75$ mm (0.257λ). The overall height of the proposed antenna is 19 mm.

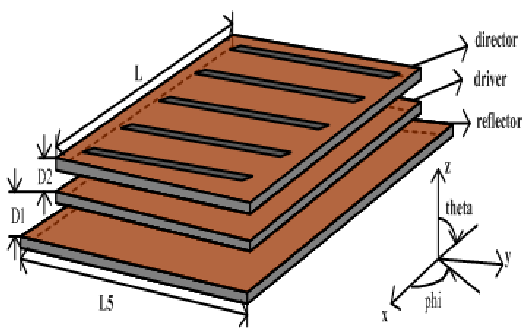


Figure 1: Structure of the proposed antenna (design 1).

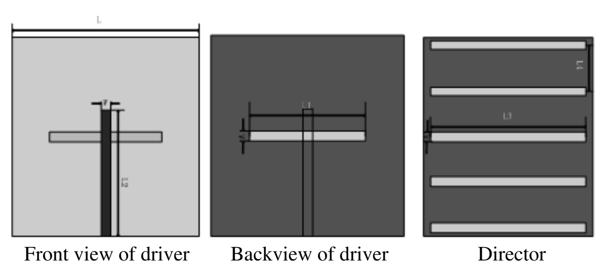


Figure 2: Structures of the proposed single layer director.

Performance of the proposed slot antenna with single-layer director is given in Fig. 3, Fig. 4 and Fig. 5. Photograph of the fabricated preliminary structure and the proposed slot antenna with single layer director is given in Fig. 3. Comparison between simulated and measured results is shown in Fig. 4 and Fig. 5. As shown in Fig. 4, the proposed slot antenna with five slots in the single-layer director has a simulated bandwidth of 21.1% and measured bandwidth of 19.6%, which exhibit wide band characteristics. Fig. 5 presents the simulated and measured *xoy* plane and *yoz* plane radiation patterns of design 1. The main lobe focuses on the orthogonal direction of the director layer (theta = 0°. Good agreement between the measured and simulated radiation

Table 1: Parameters of antenna.

Symbol	Value	Unity
H	1.5	mm
L	60	mm
$L1$	36	mm
$L2$	38	mm
$L3$	55	mm
$L4$	13.75	mm
$L5$	100	mm
W	3	mm
$D1$	11.5	mm
$D2$	6.5	mm
ε_{r1}	4.4	/
ε_{r2}	2.5	/

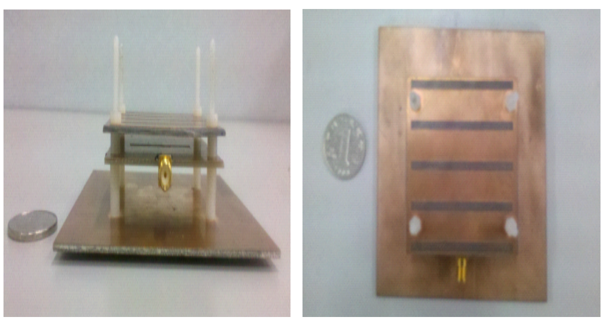


Figure 3: Photograph of the proposed slot antenna with single-layer director.

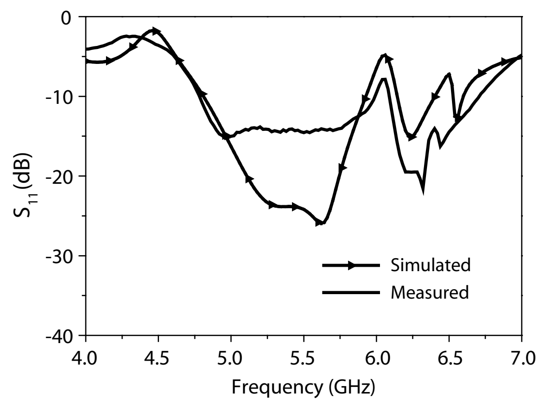
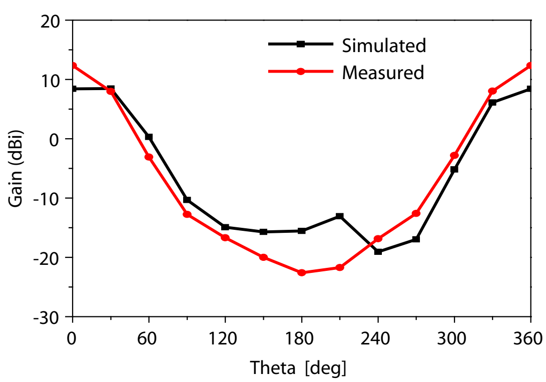
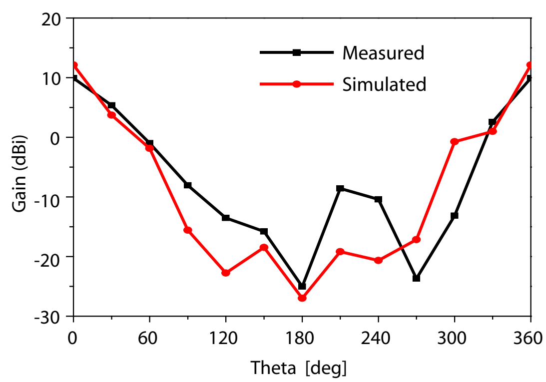


Figure 4: Simulated and measured S_{11} design 1.



(a)



(b)

Figure 5: (a) Measured and simulated radiation patterns of design 1 in xoz plane. (b) Measured and simulated radiation patterns of design 1 in yoz plane.

patterns has been achieved. The maximum simulated and measured gains are 12 dBi at 5.6 GHz and 10.4 dBi at 5.57 GHz respectively.

4. THE NOVEL SLOT ANTENNA WITH GRID STRUCTURE

In this part, a novel antenna is designed, which is named design 2. The total size of design 2 is the same as design 1, while, the gain of design 2 is enhanced. In design 2, a special structure based on SPPs is added to the preliminary antenna. The structure between the driver and director is noted as dielectric grid structure, which is shown in Fig. 6. The permittivity of this dielectric

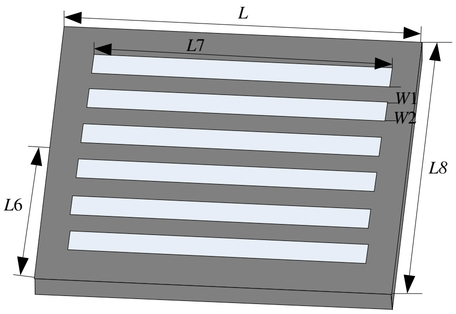


Figure 6: Structures of the proposed grid structure.

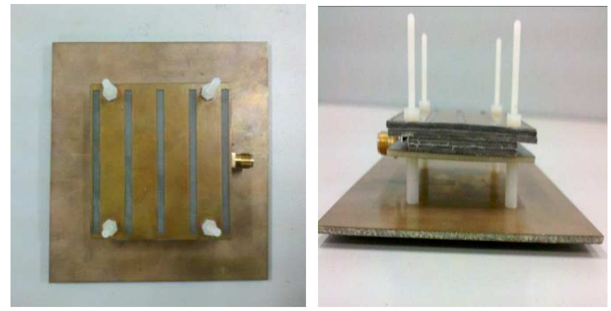


Figure 7: Photograph of design 2.

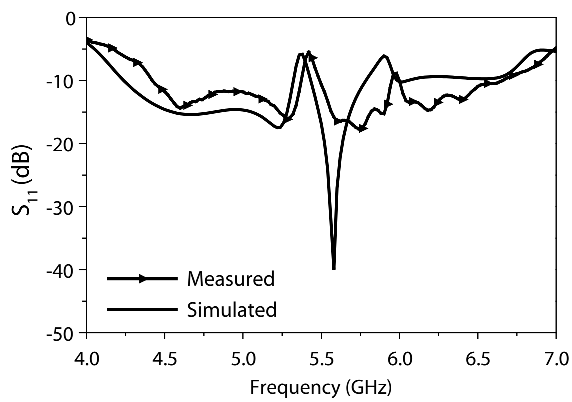


Figure 8: Simulated and measured S_{11} design 2.

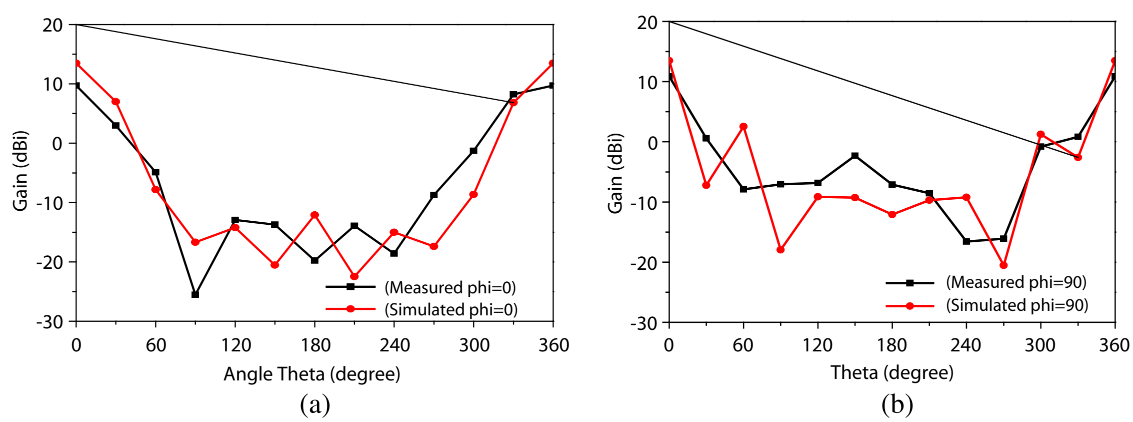


Figure 9: (a) Measured and simulated radiation patterns of design 2 in xoz plane. (b) Measured and simulated radiation patterns of design 2 in xoz plane.

is ε_{r2}. According to the surface plasmons diffraction theory, the field of electromagnetic can be enhanced [11]. Therefore, the gain of antenna can be improved. Dimensions of this grid structure are as follows: $L6 = 20.15$ mm, $L7 = 50$ mm, $L8 = 40.3$ mm, $H2 = 3$ mm. The optimized distance between the two close slots is $W1 = 1.7$ mm and the width of the slots in the grid structure is $W2 = 3.6$ mm. In design 2, some parameters are different from design 1, such as $D2 = 6$ mm, $H = 3$ mm. Other parameters are listed in Table 1.

The fabricated prototype of design 2 is shown in Fig. 7. Comparison about S_{11} between simulated and measured is shown in Fig. 8. The simulated bandwidth is 6.1% and measured bandwidth is 8.0%, which shows good agreement generally. Fig. 9 presents the simulated and measured xoy plane and yoz plane radiation patterns of design 2. The maximum simulated and measured gains are 13.5 dBi and 11.4 dBi respectively. The 2.1 dBi drop in measured gain may be caused by precision of production.

The comparison of simulated about design 1 and design 2 are discussed as following:

(a) As shown in Fig. 10, the bandwidth of design 1 and design 2 both cover frequencies from 5.49 GHz to 5.92 GHz.

(b) As shown in Fig. 11, the measured gain of design 2 is improved about 1 dBi than design 1, which is slightly lower than simulated. The measured gains of design 1 and design 2 have about 2 dBi dropped than simulated.

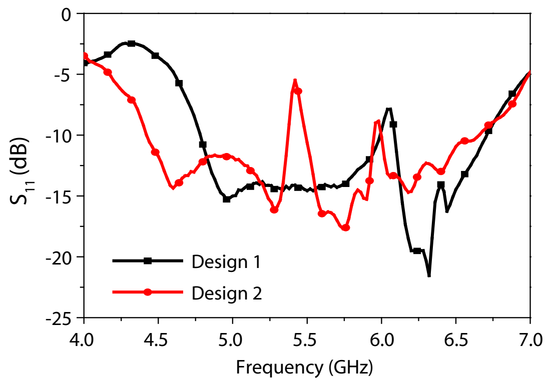


Figure 10: Measured S_{11} for design 1 and design 2.

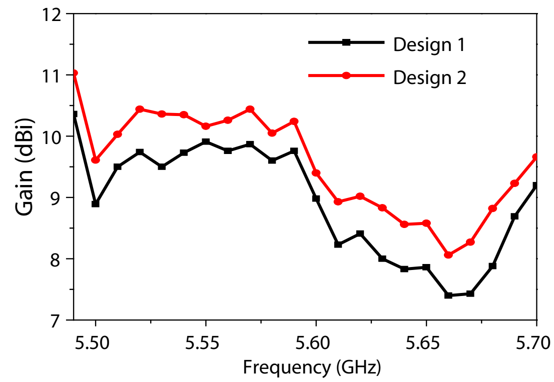


Figure 11: Measured gain for design 1 and design 2.

5. CONCLUSION

In this paper, a slot antenna with single-layer director and a novel high gain slot antenna with SPPs are proposed. By adding a substrate layer with grids structure between the driver and director of the design 1, the measured gain of the antenna is enhanced by 1 dBi. Good performance with gain of 11.4 dBi is achieved at 5.57 GHz. The overall optimum size of the proposed antenna is only $100 \times 100 \times 19\,\mathrm{mm}^3$. Good agreement between simulated and measured results is achieved.

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