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Gain Enhancement of Slot Antenna Using Grooved Structure and FSS Layer

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Abstract—This letter presents a high gain slot antenna for K-band non-contact measurement systems. The proposed antenna consists of a slot antenna on a grooved metal structure with a single frequency selective surface. In addition to a high-gain characteristic, a reduced size is strongly required for easy embedding. These features are the main objectives of this antenna design. To achieve these two objectives, an optimization procedure, based on a global algorithm, is used. Both simulation and optimization are carried out by means a full-wave electromagnetic simulation tool. Eventually, to validate the proposed design, a prototype of the antenna has been manufactured and tested. More than 15 dB of gain is measured over the operating frequency range, while optimal gain can reach 17 dB at frequency 25.5 GHz. These characteristics make this antenna very suitable for non-contact measurement, i.e., radar systems.

1. INTRODUCTION

Microwave and millimeter-wave radar systems are in continuous development [1, 2]. In addition to military and security applications, these systems are finding their way into more applications than ever thanks to technology advances that have reduced the size and production cost. For environmental applications, radar systems at microwave and millimeter-wave frequencies are suitable for non-contact measurement systems. In this context, one of the greatest and most important uses for the environment industry is the real-time water level and flow measurements. The real-time monitoring of water (and/or wastewater) may enable a rapid intervention in the case of sewage overflows, preserve rivers and lakes from any contamination, prevent flooding, etc. [3]. The antenna design for a modern radar system at microwave and millimeter-wave frequencies is a critical and challenging task which needs a strong expertise and a special attention [2–4]. High gain, high directivity, and reduced size are the most suitable features in a microwave and millimeter-wave antenna for modern radar systems. Usually, to create a high-gain antenna for radar systems, techniques based on array antenna [5–7], Electromagnetic Band Gap (EBG) or Electromagnetic meta-surface such as Frequency Selective Surface (FSS) [8, 9] and Partially Reflecting Surface (PRS) [10, 11] are widely used. Recently, slot antenna on a grooved structure has been developed in order to enhance radiation performances [12–15]. However, to achieve high-gain characteristic, the grooved structure has usually large dimensions.

In this work, we are interested in developing a high-gain antenna for radar-based non-contact measurement system in the K-band frequency range. This antenna will be integrated into a real-time wireless monitoring system for water level and flow. For this reason, in addition to the high-gain characteristic, a small size antenna is one of the important goals of this design. In this sense, we propose a novel antenna configuration consisting of a slot antenna on a grooved structure with a frequency selective surface. The use of the grooved structure enhances gain, adjusts side lobe and improves bandwidth of the antenna. However, this depends on the number of grooves and therefore the size of the structure

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(an important number of grooves implies a large structure). For this reason, we propose to substitute the large structure by introducing a frequency selective surface layer acting as a lens. Through this technique, we can use a limited number of grooves, which allows reducing the size of the antenna while achieving a high gain feature. The use of FSS is widely reported in the previous works as an efficient technique for increasing antenna gain and directivity [8]. Combining the grooved structure with an FSS lens enhances bandwidth and improves radiation performances without need to use a large structure.

In this letter, we present a high-gain slot antenna on a small size grooved structure with an FSS lens. The proposed antenna is designed for a non-contact measurement system, precisely, for the flow velocity and water level measurement. The proposed antenna has a small size and enhanced gain features. The design has been done with an optimization procedure based on a global algorithm. Simulations are carried out using full-wave electromagnetic simulation tools. Finally, a prototype of the proposed antenna is manufactured for experimental tests. The present letter is organized as follows. In Section 2, design strategy and antenna geometry are described. Next, numerical and experimental results are discussed, and finally, some conclusions are presented in Section 4.

2. ANTENNA DESIGN

A high-gain slot antenna on a grooved structure with an FSS lens is developed. Firstly, a slot antenna on a flange at the end of a rectangular waveguide is designed to operate at the frequency band 24–26 GHz. The length of a slot determines the resonant frequency, while the width of the slot determines the broad bandwidth of the slot antenna. The flange surrounding the slot can have a significant effect on the principal radiation patterns as well as cross-polarization. The flange tends to have a second-order effect on the input reflection coefficient [16]. In order to improve the radiation performance of this antenna (gain, directivity, etc.), a pair of identical grooves are incorporated in the flange surface as can be seen in Fig. 1(a). Dimensions of these grooves and the distance of each one from the slot are both optimized. This technique enhances the gain of the slot antenna, and it reaches about 11 dB. In previous work, adding grooves in the flange obtains higher gain. But usually the dimensions of the flange are important [13–15]. For integration and packaging reasons, the dimensions of the metallic flange were limited in 30 mm×30 mm. Obviously, these dimensions make the antenna's size small but cannot achieve the desired gain. In order to obtain higher gain, we propose to add a single FSS layer placed above the grooved structure. The FSS can be viewed as a flat lens, which is generally realized using planar periodic structures. Depending on the geometry, a single-layer FSS can represent a bandpass or band-stop response around its resonant frequency. For the sake of simplicity, a conventional and simple FSS layer consisting of 3×3 square patches printed on a thin RT/Duroid 5880 substrate of 0.127 mm of thickness and a relative dielectric constant of 2.2 is considered. The dimensions of each element and the distance separating these elements are carefully optimized to be operating within the frequency band 24–26 GHz. The distance separating the FSS layer and the slot antenna is an extremely important parameter which needs to be carefully determined. In Fig. 1(b), the proposed antenna with FSS layer is illustrated. The optimized value of each parameter of the proposed antenna is given in Table 1. All of these parameters are optimized by means of a global algorithm and next readjusted using a local algorithm. Simulations are carried out using a full-wave electromagnetic simulation tool.

Combining the grooved structure with an FSS layer improves radiation performances, gain and directivity, without need to use a large structure. Optimized grooves provide control of the side-lobe level and have a second-order effect on the impedance bandwidth. In the following section, we mainly discuss the versatility of this proposed technique based on simulated and experimental results.

Table 1. Value of the optimized parameters of the proposed antenna.

Parameter	L	H	L_s	W_s	h_g
Value (mm)	30.00	5.00	6.50	2.05	4.00
Parameter	I_s	d_s	h_s	d	s
Value (mm)	4.75	2.00	7.00	1.50	7.75

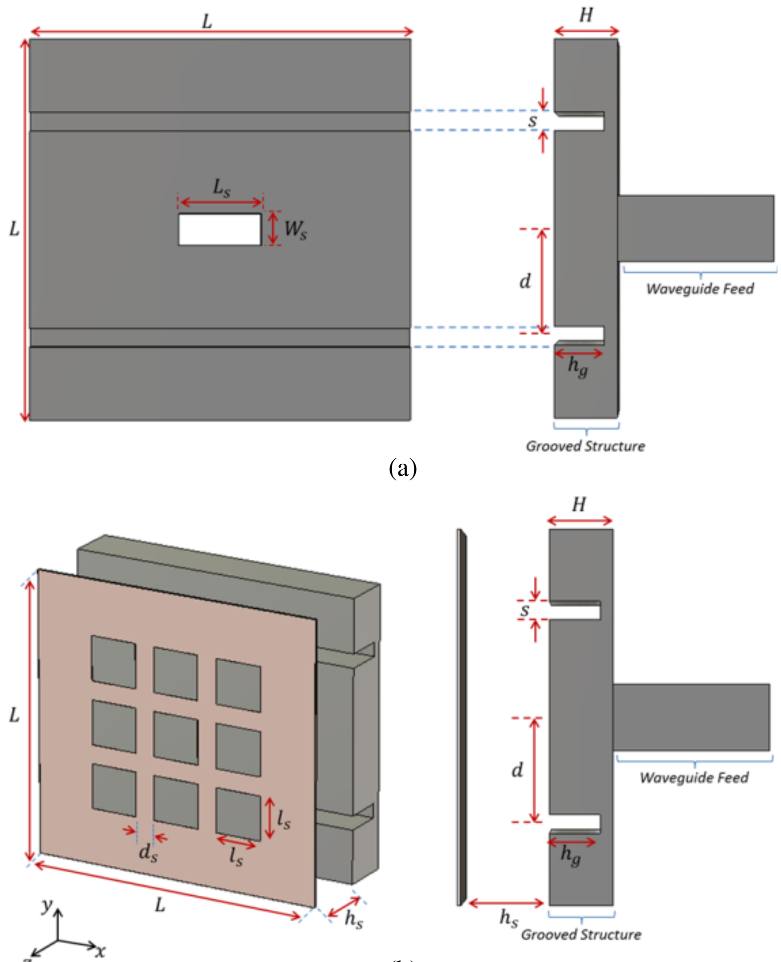

Figure 1. Geometry of the proposed antenna. (a) Slot antenna on a grooved metallic flange. (b) Slot antenna on a grooved metallic flange and FSS layer.

3. RESULTS AND DISCUSSION

In order to validate the proposed approach experimentally, a prototype of the proposed antenna was manufactured. The grooved structure was manufactured using a computer numerical control (CNC) milling process. This method produces components with high accuracy in short time and great manufacturing flexibility. The FSS layer was manufactured separately and placed above the antenna in a next step. To feed this antenna, a simple coaxial cable to waveguide transition is privileged. This technique of feeding is often used at quasi millimeter-wave frequency and beyond with the aim to reduce feeding errors and complexities. In Fig. 2, a photograph of the first prototype is illustrated. The reflection coefficient is measured and compared with the simulated results. Good agreement between measured and simulated results is obtained as can be seen in Fig. 3. The measured impedance bandwidth is about 1.13 GHz (from 24.82 GHz to 25.95 GHz) while the simulated one is about 0.97 GHz (from 24.97 GHz to 25.94 GHz). The little difference between the two curves may be due to several factors which were not taken into account during the simulation process such as the transition coaxial cable to waveguide and VNA calibration mode. In our case, the calibration of the VNA was made at the end of the coaxial cable.

The main goal of this design is obtaining a high-gain and reduced size antenna. For achieving this goal, grooves are introduced in the structure. Without grooves, the slot antenna provides about

Figure 2. Photograph of the proposed antenna. (a) Top view of the proposed antenna. (b) Side view of the antenna.

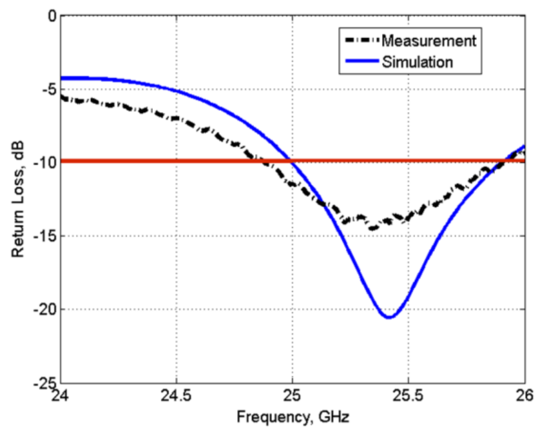

Figure 3. Comparison of the return loss of the measured and simulated results.

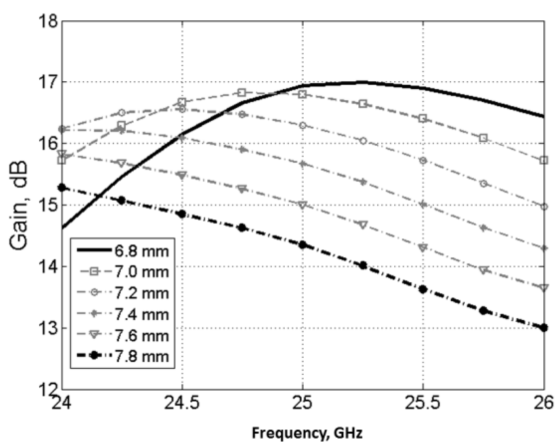

Figure 4. Simulated gain variation versus the parameter hs.

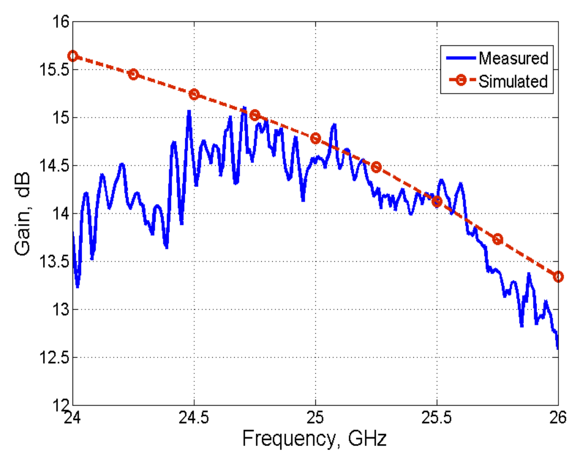

Figure 5. Measured gain compared with simulated gain results and simulated radiation.

7 dB of gain. By introducing the grooves to the structure, the gain of antenna reaches about 11 dB depending on the position and dimensions of these grooves. In some works, the antenna gain can reach more than 15 dB only by introducing the grooves in the structure. Nevertheless, the size of the grooved

structure is extensively large [15]. To maintain the feature of reduced size, a large flange is substituted by adding a single FSS layer above the antenna as described before. The distance separating the slot and the FSS layer has a strong effect on the gain result. The optimal value of this parameter reaches about 17 dB of gain as can be seen in Fig. 4. The measured gain is compared to the simulated result in Fig. 5 when a foam layer of about 7.7 mm is used to support the FSS layer. In this case, a peak of

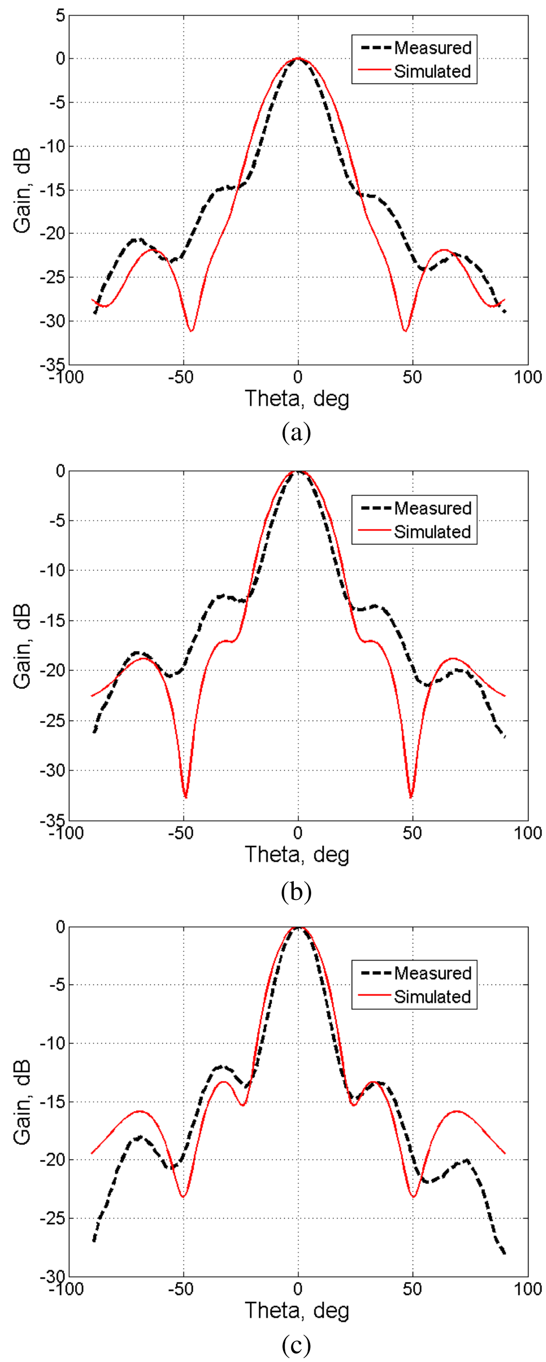

Figure 6. *H*-plane of the radiation pattern at the frequency (a) 25 GHz, (b) 25.5 GHz and (c) 26 GHz.

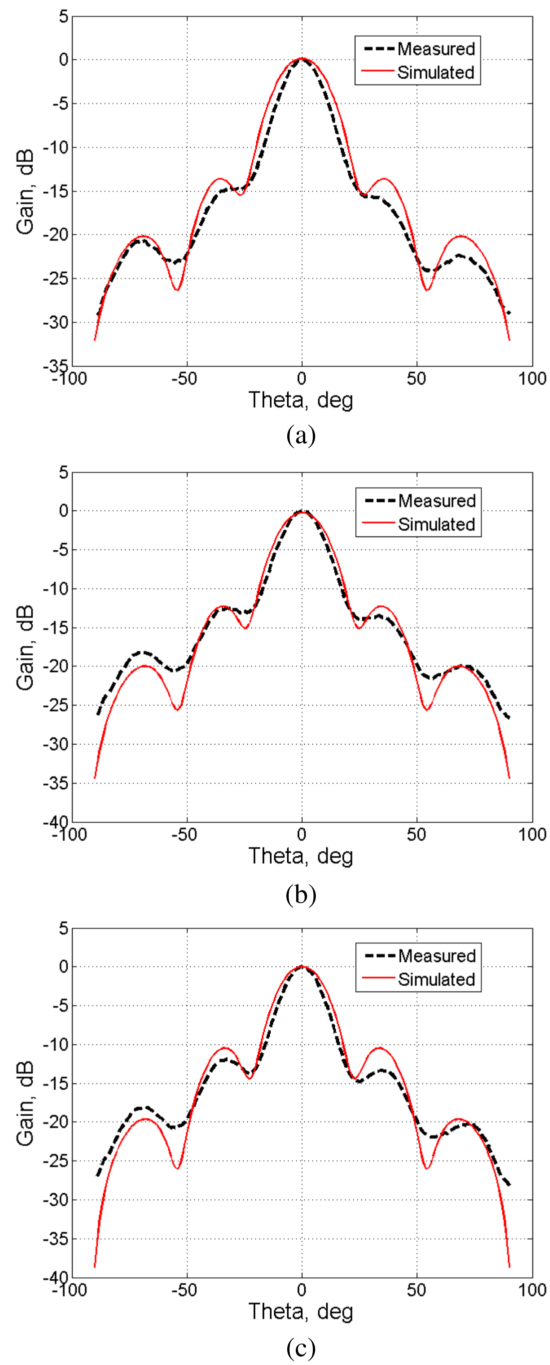

Figure 7. *E*-plane of the radiation pattern at the frequency (a) 25 GHz, (b) 25.5 GHz and (c) 26 GHz.

Table 2. Gain comparison with other works.

Reference	Antenna Size in mm	Wave length In mm	Gain In dB	HPBW E-Plane	HPBW H-Plane
[13]	65.5×40.0	20.5	16.4	18.2°	26.4°
[17]	146×18	12.5	13.87	10.88°	145°
[18]	20×14	4.87	15.6	13°	15°
[15]	60×24	17.65	10.34	-	-
This work	$\mathbf{30 \times 30}$	12.0	15.1	20.1°	22.4°

gain at 25.1 GHz is about 15 dB over the entire band. A reasonable agreement between measurement and simulation results is observed. The difference between the two around 24 GHz can be due to the transition coaxial-to-waveguide (this transition at the lower frequency band probably affects the gain characteristic). In Table 2, a comparison of the obtained gain with other works is given.

The radiation pattern of the proposed antenna is measured in an anechoic chamber. The simulated and measured radiation patterns along XZ-plane and YZ-plane of the proposed antenna are shown in Fig. 6 and Fig. 7, respectively. The measured half-power beam-widths (HPBW) along the XZ- and YZ-planes are 27.8° and 20.1°, respectively, at 25.5 GHz while the simulated values are 22.8° and 22.4°, respectively. The measured SLL peak in the XZ-plane is -11 dB at $\theta = 30°$, and the simulated one is -12.8 dB (normalized values). In the YZ-plane, the measured SLL peak is -12.5 dB at $\theta = 30°$, and the simulated value is -17.5 dB (normalized values). The difference between the measured and simulated SLL peaks is due to difference between the simulated and manufactured slots. Due to mechanical reason, the manufactured slot has a round shape. The little difference between the simulated and measured radiation patterns at the side-lobe level is due to this manufacturing difference.

4. CONCLUSIONS

In this letter, a high-gain slot antenna on a grooved structure with an FSS layer is proposed for non-contact measurement systems at the K-band frequency. The presented antenna has small size and enhanced radiation performances. A prototype is manufactured with the purpose of experimental verification of the reflection and radiation characteristics. The measured and simulated results are in good agreement. A peak of gain about 17 dB can be obtained (optimal simulated value) and more than 15 dB in measurement. The size of the proposed antenna and radiation performances make this antenna very suitable for embedded systems for non-contact measurement and short range radar systems in the K-band frequency.

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