Design and research of single-sided slotted waveguide antenna with a large beam declination

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Abstract

The slot of the conventional longitudinal slot antenna is alternately opened on both sides of the broadside. A novel single-sided slot array with a large-declination (biased towards the load) is proposed, in which the slots are only biased to the same side of the waveguide broadside. The main beam declination of a single-sided slot antenna is only biased towards the load direction and is only related to the broad-side of the waveguide. To verify the theoretical analysis, a single-sided slot array with 10-slot was simulated, fabricated, and measured. According to the measured results, the antenna achieved a beam declination of 25° and a sidelobe level below −22 dB, which is in good agreement with the theoretical analysis. Furthermore, the main beam declination of the single-sided slot and the traditional double-sided slot array has been thoroughly studied and compared. When the main beam has a large declination angle (>30°) to the load, a single-sided slot array is the only choice.

1 | INTRODUCTION

In the conformal antenna of some missiles, the main beam of the antenna and the normal direction of radiating surface need to have a certain declination, which requires a traveling-wave array antenna [1]. Among them, the waveguide longitudinal slot array is one of the commonly used types. The longitudinal slot array has the advantages of high gain, low or even ultra-low sidelobe level (SLL), high power capacity, low profile, high radiation efficiency, and easy control of the pattern [2–4]. Over the past decades, waveguide longitudinal slot antennas have been verified by numerical calculations, theoretical research, and experimental methods. Among them, many analysis methods are often used, such as Elliott’s design procedure [2,5], full-wave analysis method [6], numerical simulation method [4].

The conventional longitudinal slot antenna has a slot spacing centred at \( \lambda_g/2 \), and the slots are alternately opened on both sides of the centre of the wide side of the waveguide, where \( \lambda_g \) is the wavelength in the waveguide. In general, the conventional waveguide slot arrays are generally classified into two types: standing-wave arrays and traveling-wave arrays [3]. In the standing-wave arrays, the radiating slot spacing is \( \lambda_g/2 \), and the waveguide antenna is shorted at \( \lambda_g/4 \) after the last slot. The radiation pattern is strictly broadside and symmetric, but the operating bandwidth is relatively narrow. For the traveling-wave array, the slot spacing is not equal to \( \lambda_g/2 \) (more or less than \( \lambda_g/2 \)), and the end of the waveguide is absorbing load. The main beam of the pattern has an inclination angle, and the inclination angle changes with frequency.

However, when a large declination (> 20°) is biased towards the load, the conventional slot array requires a larger slot spacing (even greater than \( \lambda_0 \)), and such the conventional slot array is not suitable, where \( \lambda_0 \) is the wavelength in free space. In addition to conventional waveguide slot antennas, slot antennas based on substrate integrated waveguides (SIW) have also been extensively investigated [7,8]. The transmission performances of the SIW are very similar to those of a metallic rectangular waveguide [9–11]. Hosseininejad et al. [12] showed a traveling-wave SIW slot array antenna with an off-angle of 25° by performing the Method of Least Squares (MLS). In Ref. [13], an SIW slot antenna with a main beam declination of 26° and a sidelobe level (SLL) below −20 dB in Ka-band was represented. The above SIW-based slot antenna can achieve a large main beam declination (~25°). However, the slot antenna...
using the SIW form has greater energy leakage and dielectric loss, so the antenna radiation efficiency is lower than that of the hollow waveguide type. In addition, as the declination angle increases, the slot spacing also increases, so it is difficult to achieve a larger declination (>30°). Therefore, the implementation of a large declination (biased towards the matching load) slot antenna is a problem that needs to be solved.

A novel single-sided longitudinal slot array antenna with large declination was proposed. In contrast to conventional longitudinal slot antennas, the slots are all on the same side of the centre of the waveguide broadside. In addition, the main beam declination of the single-sided slot array is only biased towards the matching load. To verify the design, a single-sided slot array with 10-slot is designed, fabricated and measured. According to the measured results, the antenna achieved a beam declination of 25° and a SLL below −22 dB, which is in good agreement with the theoretical analysis. Furthermore, combined with the array theory, the declination of the single-sided slot array is deeply studied, and the achievable ranges of the declination and the slot spacing are given. The declinations of the single-sided slot array and the double-sided slot array are also compared and discussed. At the same time, the best choices under different declinations are provided.

2 | DESIGN OF SINGLE-SIDED ARRAY

The geometry of the single-sided traveling-wave slot array antenna is illustrated in Figure 1. Basically, the antenna consists of three parts, a waveguide, a coaxial port, and a matched load. There are 10 radiation slots in waveguide along yoz-plane. In contrast to conventional longitudinal slot array, the 10-slot here are offset on the same side of the waveguide broadside. In order to clearly describe the design process of a single-sided slot antenna, Section 2 is divided into three parts. The calculation method for the declination of the single-sided slot array is discussed in Section 2.1. The design of SLL of slot array is discussed in Section 2.2. The waveguide coaxial conversion part and the overall design of the antenna are given in Section 2.3.

2.1 | Design of the beam declination \( \theta_M \)

The single-sided slot array is one type of traveling-wave slot arrays, so the main beam will change with frequency. Therefore, the main beam declination at a single frequency is considered. The schematic diagram of the single-sided slot array is shown in Figure 2.

According to the waveguide theory [2,14], the wavelength propagating in the waveguide is \( \lambda_g \), and \( \lambda_a \) is solved as follows:

\[
\lambda_a = \frac{\lambda_0}{\sqrt{1 - \left(\frac{d_s}{a_s}\right)^2}} = \frac{\lambda_0}{\sqrt{1 - \left(\frac{d_s}{\lambda_0}\right)^2}}
\]  

(1)

where \( a \) is the width of the broadside of waveguide, and \( \lambda_c = 2a \) is the cutoff wavelength in waveguide [14].

As shown in Figure 2, the spacing between adjacent slots is specified as \( d \), so the phase difference \( \phi \) between adjacent slots is as follows:

\[
\phi = \frac{d}{\lambda_a} \times 2\pi
\]

(2)

According to the theory of electromagnetic waves, the array main beam propagates along the normal direction of the equal phase plane. Therefore, the main beam will be biased towards \( \theta_M \) only if the leading phase in free-space is equal to the lagging phase in the waveguide. The corresponding leading distance \( s \) in free-space is as follows:

\[
s = \frac{\phi}{2\pi} \times \frac{\lambda_0}{d} = d \times \sin \theta_M
\]

(3)

According to Equation (3), the corresponding beam declination is:

\[
\theta_M = \arcsin \left(\frac{\phi}{2\pi} \times \frac{\lambda_0}{d}\right)
\]

(4)
Combining Equations (1) and (4) can be obtained as follows:

\[
\theta_M = \arcsin \left( \frac{\lambda_0}{2a} \right) = \arcsin \sqrt{1 - \left( \frac{\lambda_0}{2a} \right)^2} \tag{5}
\]

It can be seen from Equation (5) that the declination of the main beam is only related to the broadside of the waveguide at the specified frequency. Also, \(\lambda_0\) is always smaller than \(\lambda_c\), so the main beam is only biased towards the load. Here, the operating frequency \(f = 38.5\) GHz, \(\theta_M = 25^\circ\). According to the Equation (5), the width of the waveguide broad side \(a = 4.3\) mm, \(b = 2\) mm. Combined with the requirements of antenna installation size, the length of slot array is less than 70 mm. At the same time, considering the absorbing load and the size of the waveguide coaxial converter, the number of slots is selected as 10.

2.2 Design of the SLL

SLL is an important parameter in slot array antennas, which requires radiating energy synthesis for each slot. The radiation energy of each slot is related to the distance of the slot from the centre of the broadside. According to waveguide theory [14], the larger the slot offset is, the stronger the radiant energy (conductance) is. However, there is internal and external coupling between the slots, so the coupling effect must be considered when calculating the radiated conductance of the slot.

The relationship between slot offset and conductance value is obtained by simulating the slotted waveguide array. Each type of slot array has the same slot offset, thereby obtaining a conductance under a slot offset [4,13]. Through the relationship between the S parameter, slot offset and slot length, the corresponding radiation conductance value can be obtained. Since there is an internal and external coupling between the radiating slots, in order to include the conductivity value of the coupling between adjacent slots, the number of slots is generally greater than 10. This method is simple and easy to implement. The geometry of slot antenna is shown in Figure 3.

When the slot offset is given and the slot length is resonant, the relationship between the corresponding radiated conductance and S-parameter is shown in Equation (6) [15].

\[
g = 1 - q \times \left( \frac{|S_{21}|^2}{1 - |S_{11}|^2} \right) \tag{6}
\]

where \(S_{21}\) is the transmission coefficient between two ports, \(S_{11}\) is the reflection coefficient of port 1, \(N\) is the number of slots, and \(q = 0.999\) is the attenuation coefficient between two adjacent slots (waveguide made of aluminum).

Combined with high frequency structure simulator (HFSS) software, the 10-slot with the same offset are simulated. The antenna is set to dual port in simulation, where the coaxial port is port one and the matching load is port 2, as shown in Figure 3.

Under the same slot offset, the slot length at which the transmission coefficient \((S_{21})\) of the centre frequency \((f = 38.5\) GHz) resonates is the resonance length. Then, the conductivity value corresponding to the slot offset can be obtained by Equation (6). The simulated S-parameters, conductance and resonant lengths are shown in Table 1.

To obtain a low SLL, the Taylor synthesis is often adopted in the amplitude distribution of the slot array. It is well known that the greater the number of slots, the easier it is to achieve a lower SLL. Here the number of slots is small, and SLL = −23 dB is taken as an example. The normalized current and conductance distribution of each slot is shown in Figure 4. In Taylor synthesis, the current distribution of each slot is symmetric about the intermediate slot, but the conductance of each slot is asymmetrical. The reason is that in the traveling-wave array, as the front slot radiates energy, the total energy radiated by the following slot is gradually decreasing. Therefore, the slot conductance near the feed is small, and the conductance near the load is large, thus ensuring that the overall radiation is symmetrical.

According to the Table 1 and Figure 4, the offset and the resonance length of each slot can be given. Owing to the mutual coupling of the inner slots and the outer slots is different, the Equation (6) gives the conductance value of the inner slots. So the conductance values of the outer slots need to be optimally adjusted to obtain the best results. The final parameters of the slot are determined as follows (unit: mm): \(L_1 = 3.96, L_2 = 3.96, L_3 = 3.96, L_4 = 3.97, L_5 = 3.97, L_6 = 3.97, L_7 = 3.97, L_8 = 3.97, L_9 = 3.97, L_{10} = 3.96, Y_1 = 0.11, Y_2 = 0.17, Y_3 = 0.22, Y_4 = 0.32, Y_5 = 0.37, Y_6 = 0.43, Y_7 = 0.41, Y_8 = 0.37, Y_9 = 0.35, Y_{10} = 0.33, W = 0.65\).

2.3 Design of coaxial to waveguide converter

The excitation of waveguide slot antennas is generally divided into waveguide feed or coaxial feed. For a compact design, the antenna is fed through a 50-\(\Omega\) coaxial line, shown in Figure 5. The conversion from coaxial to waveguide is the conversion of the TEM mode in the coaxial to the \(TE_{10}\) mode in the waveguide [14,16]. The coaxial feeding line adopts a glass insulator, and the dimensions of the coaxial outer and inner conductors are \(D_1 = 1.6\) mm, \(D_2 = 0.3\) mm, and the dielectric constant of the insulating part is 4.97. When the antenna is actually assembled, one end of the coaxial inner conductor is inserted into the waveguide, and the other end is directly connected to the receiving circuit plate, as shown in Figure 7b. Combined with the simulation software HFSS, the final parameters of the coaxial conversion are determined as follows.

**FIGURE 3** Geometry of the single-sided slot array antenna

![Diagram of single-sided slot array antenna](image-url)
Table 1: S-parameters, resonant conductance and resonant length against the slot offset at centre frequency (38.5 GHz)

| Slot Offset (mm) | $S_{21}$ (dB) | $S_{11}$ (dB) | Resonant Conductance | Resonant Length (mm) |
|------------------|---------------|---------------|----------------------|----------------------|
| 0.05             | -0.35         | -32           | 0.017                | 3.97                 |
| 0.1              | -1.5          | -35.1         | 0.068                | 3.97                 |
| 0.12             | -2            | -35.3         | 0.089                | 3.97                 |
| 0.15             | -2.2          | -33.6         | 0.097                | 3.97                 |
| 0.18             | -4.6          | -30.5         | 0.19                 | 3.97                 |
| 0.2              | -5.68         | -28.9         | 0.23                 | 3.97                 |
| 0.22             | -6.85         | -26.6         | 0.27                 | 3.97                 |
| 0.25             | -8.7          | -24.4         | 0.33                 | 3.97                 |
| 0.28             | -10.65        | -22.4         | 0.39                 | 3.97                 |
| 0.3              | -12.2         | -21           | 0.43                 | 3.97                 |
| 0.32             | -13.45        | -20.3         | 0.46                 | 3.97                 |
| 0.35             | -15.9         | -18.4         | 0.52                 | 3.97                 |
| 0.38             | -18.13        | -17.2         | 0.57                 | 3.97                 |
| 0.4              | -20.18        | -16.3         | 0.61                 | 3.98                 |
| 0.45             | -24.7         | -14.7         | 0.68                 | 3.99                 |
| 0.5              | -29.6         | -13.1         | 0.74                 | 4.0                  |

Figure 4: Equivalent conductance and normalized current of each slot with the number of slots $N = 10$ (Taylor synthesis of SLL = -23 dB).

Figure 5: Cross-section view of the single-sided slot array and the geometry of the coaxial port.

( unit: mm): $H = 1.04$, $S_0 = 2.05$. The simulated S-parameter of the coaxial to waveguide conversion is shown in Figure 6. As seen in Figure 6, the transmission performance is particularly good within the operating frequency bandwidth.

For the above three calculations and simulations, the slot array antenna and waveguide coaxial conversion have been simulated as a whole in HFSS. According to the optimal design, the antenna is fabricated and tested to verify the accuracy of the design.

3 | Experimental Verification and Discussion

The photograph of the single-sided slot antenna is pictured in Figure 7. The antenna prototype is designed as a single port for compactness, the coaxial port is the input port, and the other end is directly connected to a matching load.
Agilent Vector network analyser 8722ET is used to measure the reflection coefficient of the proposed antenna, and is shown in Figure 8. The impedance bandwidth of the antenna is very wide with a reflection coefficient less than −18 dB, and the simulated and the measured results have a good agreement. Since the antenna sample is a single port, only the reflection coefficient $S_{11}$ of the port one can be tested, and the transmission coefficient $S_{21}$ cannot be measured. From the simulated $S_{21}$, the transmission coefficient is about 5.2% (−12.8 dB), and the antenna radiation efficiency is greater than 94%. In addition, the broadside of the waveguide $a = 4.5$ mm, and the corresponding cutoff frequency $f_c = 34.88$ GHz. According to the simulated results, the cutoff frequency is about 35 GHz, which is in line with the theory.

The radiation pattern, gain, and beam declination of the slot array are also measured by a far-field measurement system. The theoretical, simulated, and measured beam declination and SLL in the H-plane are shown in Table 2. The simulated and measured results are in good agreement with the theoretical analysis. Figure 9 shows the simulated and measured radiation patterns at frequencies of 38, 38.5, and 39 GHz. The E-plane is the $xoy$-plane and the H-plane is the $yoz$-plane, as shown in Figure 1. From the comparison results, the overall trend is very consistent, but there are still some deviations. The reason of the deviation should be attributed to the inaccuracy of the simulated internal and external mutual coupling between the slots, the error of the slot processing, and the test environment. At the same time, as the frequency increases, the grating lobe level gradually increases. Nevertheless, all grating lobe levels are below −24 dB.

The simulated and measured gains for several frequencies are illustrated in Figure 10. It can be seen that the measured gain is about 14.1 ± 0.1 dBi, which is slightly lower than the simulated gain of 14.85 ± 0.1 dBi. The deviation is mainly attributed to the loss of coaxial to waveguide conversion, processing inaccuracy of the slots, and the influences of the test environment.

## 4 | COMPARISON BETWEEN SINGLE-SIDED AND DOUBLE-SIDED ARRAY WITH SIMILAR LENGTHS

A single-sided slot array is proposed and fabricated as a replacement for the double-sided slot array being serviced. Based on the simulation and measurement in Sections 2 and 3, the single-sided slot array achieves better radiation performance in terms of radiation efficiency and SLL. And the law of the main beam declination angle of the single-sided slot array and the double-sided slot array is completely different. Therefore, the declination characteristics and declination angle range of the two types of slot arrays are analyzed and compared. Figure 11 shows three types of slot antennas, which are single-sided slot antennas, double-sided slot antennas with SIW structure [13], and double-sided slot antennas filled with teflon medium. Among the three types, the single-sided slot
To give a clear comparison of the declination $\theta_M$ of the two types of slot arrays, Section 4 is divided into four parts. Section 4.1 is the derivation of the declination angle the double-sided slot array, Section 4.2 is the declination angle range of the single-sided slot array, Section 4.3 is the declination angle range of the double-sided slot array, and Section 4.4 gives the selection of the slot antenna at different declination angles.

### 4.1 Calculation of declination $\theta_M$ of double-sided slot array

The waveguide longitudinal slot antenna is a very common high-efficiency antenna. There are two types depending on the offset position of the slots: one is alternately biased on both sides of the waveguide centre, and the other is biased on a single-sided of the centre of the waveguide. In the first type of slot array, there is a phase inversion between adjacent slots, that is, an additional phase difference $\pi$. Therefore, with reference to Figure 2 and Equations (2)–(4), the maximum radiation angle of the double-sided slot array can be obtained as follows:

$$\frac{2\pi}{\lambda_0} d \times \sin \theta_M = \frac{2\pi}{\lambda_g} d - \pi \quad (7)$$

---

**FIGURE 9** Simulated and measured radiation patterns. (a) 38 GHz, (b) 38.5 GHz, (c) 39 GHz

**FIGURE 10** Simulated and measured gains of the single-sided slot array with 10-slot array has the lowest processing cost and the most stable performance.
According to Equations (10) and (11) can only be:

\[
\sqrt{1 - \left(\frac{\lambda_0}{2d}\right)^2} - \frac{\lambda_0}{2d} > -1
\]

(12)

Simplifying Equation (12), the lower limit of the spacing \( d \) can be obtained as follows:

\[
d > \frac{\lambda_0}{\sqrt{2}} \left(1 - \frac{1}{\sin\left(\sqrt{1 - \left(\frac{\lambda_0}{2d}\right)^2} - \frac{\lambda_0}{2d}\right)}\right)\]

(13)

When the number of slots is infinite, the upper limit of the spacing \( d \) can refer to Equation (10). However, when the number of slots is limited, the Equation (10) is not accurate enough. Therefore, substituting Equation (8) into Equation (9) can get:

\[
d < \frac{\lambda_0}{1 + \sin\left(\sqrt{1 - \left(\frac{\lambda_0}{2d}\right)^2} - \frac{\lambda_0}{2d}\right)}\]

(14)

In general, the slot length is about half a wavelength, and the slots are alternately opened on both sides of the centre of the waveguide. Therefore, in order to ensure that the slots are not connected, the slot spacing must be greater than a quarter wavelength, as follows:

\[
d > \frac{\lambda_0}{4}
\]

(15)

Substituting Equation (15) into Equation (14), the upper limit of \( d \) can be derived:

\[
d < \frac{\lambda_0}{1 + \sin\left(\sqrt{1 - \left(\frac{\lambda_0}{2d}\right)^2} - \frac{\lambda_0}{2d}\right)}\times \left(1 - \frac{1}{2N}\right)
\]

(16)

Next, the range of main beam declination \( \theta_M \) is discussed. Substituting Equation (13) into Equation (8), the lower limit of the declination is:

\[
\theta_M > \arcsin(-1) = -90^\circ
\]

(17)

Substituting Equation (10) into Equation (8), the upper limit of the declination is:

\[
\theta_M < \arcsin\left(\sqrt{1 - \left(\frac{\lambda_0}{2d}\right)^2} - \frac{1}{2}\right)
\]

(18)
Equation (18) is an approximation of the limit case where the number of slots \( N \) is infinite.

To verify the above deduced formulas, the simulated verification is given in combination with HFSS. The centre operating frequency is 38.5 GHz, the waveguide type is adopted an EIA international standard waveguide type WR22 \((a = 5.69 \text{ mm}, b = 2.845 \text{ mm}, \lambda_0/2a = 0.68)\), the number of slots is \( N = 10 \). According to Equation (18), the upper limit of declination is \( \theta_M < 13^\circ \), where the number of slots \( N = \) infinite. Therefore, the declinations \( \theta_M = -60^\circ, -45^\circ, -30^\circ, -15^\circ, 0^\circ, 13^\circ \) were simulated. From the simulated radiation patterns, when \( \theta_M = 13^\circ \), the grating lobes cannot be suppressed, as shown in Figure 12b.

It can also be seen from Figure 12a that: (a) The lower limit of the spacing is, which is consistent with the Equation (15). (b) Under the same waveguide, as the slot spacing increases, \( \theta_M \) gradually increases (the beam gradually shifts from the feeding port to the matching load). (c) At the same frequency, the range of \( \theta_M \) becomes smaller as the width of the waveguide broadside decreases. (d) When \( \theta_M > -45^\circ \), the simulated \( \theta_M \) is in good agreement with the Equation (8). However, when \( \theta_M < -45^\circ \), the simulated \( \theta_M \) begins to deviate from the Equation (8). The reason is that the coupling between the slots is strong at a large declination, and the number of slots is small.

When a waveguide is filled with a medium, the wavelength propagating in the waveguide is reduced to a multiple of \( \epsilon_r \), to the power of 0.5, where \( \epsilon_r \) is the dielectric constant of the medium. Therefore, the slot antenna of the SIW form can obtain a larger declination angle (towards the load end). The formula for the beam declination angle of the medium-filled waveguide slotted antenna is shown in Equation (19). According to the research in Refs. [11–13], the maximum declination angle of the main beam that can be achieved using the SIW technology is about \( 30^\circ \). At larger declination angles, the grating lobes deteriorate.

\[
\theta_M < \arcsin \left( \sqrt{1 - \left( \frac{\lambda_0}{2a\sqrt{\epsilon_r}} \right)^2} \right) - \frac{1}{2} \tag{19}
\]

4.3 | Discussion on the ranges of spacing \( d \) and declination \( \theta_M \) in the single-sided slot array

According to Equation (5), in a single-sided slot array antenna, the slot spacing does not affect the declination angle of the main beam. But there are some other factors that need to be considered in the selection of the slot spacing. The length of the slot is about half a wavelength, so the slot spacing must be greater than half a wavelength:

\[
d > \frac{\lambda_0}{2} \tag{20}
\]

In addition, since the grating lobes of the array patterns need to be suppressed, the maximum size of the slot spacing \( d \) needs to satisfy Equation (9).

To verify the above theoretical analysis, Figure 13 shows the simulated patterns at different slot spacings. The operating frequency \( f = 38.5 \) GHz, the wavelength \( \lambda_0 = 7.79 \) mm, the width of the waveguide broadside \( a = 4.3 \) mm, the number of slots \( N = 10 \). According to the Equations (5), (20), and (9), \( \theta_M \)
= 25°, and the range of the slot spacing \( d \) is: 3.9 mm < \( d \) < 5.2 mm. The simulation patterns of the slot spacing \( d = 4.5, 5.2, 6, 7, 7.79 \) mm are given. From the simulated results, as the slot spacing changes, the declination of the main beam does not change (all are \( \theta_M = 25° \)), which is in good agreement with Equation (5). When \( d < 5.2 \) mm, the grating lobes were significantly suppressed. However, when the spacing \( d > 5.2 \) mm and gradually increases, the grating lobes become more and more prominent. This is also in accordance with Equation (9).

Next, the range of the main beam declination is discussed. According to Equation (5), the range of \( \theta_M \) can be from 0° to 90°, which is practically impossible to achieve. Considering the suppression of the grating lobes, combined with Equations (20) and (9), the following can be obtained:

\[
\frac{\lambda_0}{2} \leq \frac{\lambda_0}{1 + \sin \theta_M} \times \left(1 - \frac{1}{2N}\right)
\]  

To simplify the Equation (21), the upper limit of \( \theta_M \) can be find:

\[
\sin \theta_M < 1 - \frac{1}{N}
\]  

(22)

Substituting Equation (22) into Equation (5), the upper limit of \( \alpha \) can be derived:

\[
a < \frac{\lambda_0}{2} \times \frac{1}{\sqrt{1 - \left(1 - \frac{1}{N}\right)^2}}
\]  

(23)

It is known that the cutoff wavelength of the waveguide is \( \lambda_c = 2a \), where \( \lambda_0 < \lambda_c \), and \( a > \lambda_0/2 \) can be obtained. Therefore, the range of \( \alpha \) can be given as:

\[
\frac{\lambda_0}{2} < a < \frac{\lambda_0}{2} \times \frac{1}{\sqrt{1 - \left(1 - \frac{1}{N}\right)^2}}
\]  

(24)

Similarly, the range of declination of main beam can be obtained as follows:

\[
0 < \theta_M < \arcsin \left(1 - \frac{1}{N}\right)
\]  

(25)

From the above analysis, the range of the beam declination depends on the number of radiation slots, and the larger the number, the larger the declination range.

To verify the above discussion, an array antenna with 10-slot was exemplified. According to Equation (25), the range of \( \theta_M \) is: \( 0° < \theta_M < 64.1° \), as shown in Figure 14a. However, the upper and lower limits of the beam declination in Equation (25) cannot be implemented in engineering, for the following reasons:

a. When the beam declination \( \theta_M \approx 0° \), \( \lambda_0/(2a) \approx 1 \), the wavelength is close to the cutoff wavelength, so the transmission characteristics of the waveguide are poor. In this case, the change of \( a \) is very sensitive to the beam declination (in other words, a small change of \( a \), \( \theta_M \) will be greatly deviated, as shown in Figure 14a), so it is difficult to achieve an accurate \( \theta_M \) value in engineering. Therefore, the lower limit of the \( \theta_M \) is generally chosen as follows:

\[
\theta_M > 10°
\]  

(26)

When \( \theta_M < 10° \), the double-sided slot array is the best implementation. For detailed analysis, see Section 4.2.

b. When \( \theta_M \) is close to the upper limit, considering the suppression of the grating lobes, the slot spacing is very small (each slit is almost connected). Therefore, the mutual coupling between the slots is very large. To verify the achievability of the \( \theta_M \) upper limit, the array was simulated in HFSS. The operating
| Antenna Type                  | Declination $\theta_M$ | Slot Spacing $d$ | Formula                      |
|-------------------------------|-------------------------|-----------------|------------------------------|
| Double-sided slot array       | $\theta_1 : -90^\circ < \theta_M < 0^\circ$ | $d < \lambda_L/2$ | Equation (17) |
|                               | $\theta_2 : \theta_M = 0^\circ$ | $d = \lambda_L/2$ | Equation (18) |
|                               | $\theta_3 : 0^\circ < \theta_M < 10^\circ$ | $d > \lambda_L/2$ | Equation (18) |
|                               | $\theta_4 : \theta_M < 30^\circ$ with SIW | $d > \lambda_L/2$ | Equation (19) |
| Single-sided slot array       | $\theta_5 : 10^\circ < \theta_M < 60^\circ$ |                        | Equations (9) and (20) |
|                               | $\theta_6 : \theta_M > 60^\circ$ |                        | Equations (26) and (27) |

### Table 3: Best choice of arrays with different main beam declination angles. The descriptions of $\theta_0$, $\theta_1$, $\theta_2$, $\theta_3$ are shown in Figure 15.

### Table 4: Various characteristics of antennas in Refs. [11–13] compared with the proposed one. ($\lambda_L$ represents the wavelength of the centre frequency)

| Ref.  | Antenna Type                  | Declination $\theta_M$ | Slot Spacing $a$ (mm) | Broadside $a$ (mm) | $F_0$ (GHz) | Number of Slots | Gain (dBi) | SLL (dB) |
|-------|-------------------------------|-------------------------|-----------------------|-------------------|-------------|-----------------|------------|---------|
| [11]  | Double sided with SIW, $e_r = 2.65$ | 20$^\circ$             | 0.54                  | 6.5               | 24          | 16              | 17.5       | 21      |
| [12]  | Double sided with SIW, $e_r = 2.94$ | 25$^\circ$             | 0.633                 | 13.048            | 10          | 10              | 13.4       | 17      |
| [13]  | Double sided with SIW, $e_r = 2.2$ | 26$^\circ$             | 0.615                 | 5.6               | 35.5        | 13              | 12.7       | 20      |
|       | Double sided with SIW, $e_r = 2.2$ | 35$^\circ$             | 0.84                  | 5.2               | 38.5        | 10              | 11         | 17      |
|       | Double sided with hollow waveguide | 20$^\circ$             | 1.01                  | 7.112             | 38.5        | 10              | 12.8       | 14      |
|       | Double sided with hollow waveguide | 25$^\circ$             | 1.21                  | 7.112             | 38.5        | 10              | 12.7       | 13.5    |
| Proposed | Single sided with hollow waveguide | 25$^\circ$             | 0.64                  | 4.3               | 38.5        | 10              | 14.1       | 22.3    |
|       | Single sided with hollow waveguide | 35$^\circ$             | 0.64                  | 4.76              | 38.5        | 10              | 13.4       | 18      |
|       | Single sided with hollow waveguide | 51$^\circ$             | 0.64                  | 6.2               | 38.5        | 10              | 12.2       | 16      |

frequency $f = 38.5$ GHz, the number of slots $N = 10$, and the declination $\theta_M = 10^\circ$, $15^\circ$, $25^\circ$, $30^\circ$, $35^\circ$, $45^\circ$, $51^\circ$, $60^\circ$. When $\theta_M > 51^\circ$, the simulated $\theta_M$ deviates from the theoretical value, and the grating lobes cannot be suppressed, as shown in Figure 14a,b. Based on the simulated results and engineering achievability, the upper limit of $\theta_M$ is recommended as follows:

$$\theta_M \leq 0.8 \times \arcsin \left(1 - \frac{1}{N}\right) \quad (27)$$

According to Equations (26) and (27), the achievable ranges of $\theta_M$ is: $10^\circ < \theta_M < 51^\circ$, as shown in Figure 14a. As the number of slots increases, $\theta_M$ can obtain a larger range of declination. If the size of $a$ can be changed quickly and accurately, the main beam declination can be easily adjusted. Therefore, a single-sided longitudinal slot array is a natural large-angle beam scanning antenna.

### 4.4 Selection of the slot antenna at different declination $\theta_M$

Based on the analysis in Sections 4.1–4.3, the two types of slot arrays correspond to different main beam declination angles. The best choice of slot antennas at different declinations is shown in Table 3. It can be seen from Table 3 that when the main beam has a large declination angle, the single-sided slot array has an irreplaceable role.

Table 4 shows the comparison between the proposed single-sided slot array and other types of antennas. It can be seen from Table 4 that the antennas in Refs. [11–13] are based on the bilateral slot array of SIW form, and its maximum main beam declination angle is between 20$^\circ$ and 26$^\circ$. If the declination angle is larger, the slot spacing increases, and the grating lobe is very obvious. In addition, the slot antenna using the SIW form has greater energy leakage and dielectric loss [12,13], so the antenna radiation efficiency is lower than that of the hollow waveguide type. If a double-sided slot array with hollow waveguide is used, the slot spacing is greater than one wavelength at the declination angle $\theta_M = 20^\circ$ and 25$^\circ$, which will cause the grating lobe to be very obvious. However, in a single-
sided slot array with declination angles of 25°, 35°, and 51°, only the wide side is different, and the slot spacing does not change, as shown in Figure 14b. From the above comparison, it is shown that when the main beam has a large declination angle ($\theta_M > 30°$), a single-sided slot array is the only choice.

5 | CONCLUSION

This paper presents a single-sided slot array antenna with a large declination angle. The single-sided slot array has obvious advantages at large declination angles (biased to the load). To verify the theoretical analysis, a single-sided slot array with 10-slot was fabricated and measured. According to the measured results, the antenna achieved a beam declination of 25° and a SLL below −22 dB, which is in good agreement with the theoretical analysis. Thus verifying the correctness of the analytical methods and the derivation formulas. Furthermore, the ranges of the declination and slot spacing were given. The beam declination of the single-sided slot array and the double-sided slot array are also discussed and compared. At the same time, the best choice of slot array at different declinations is provided. The slot arrays are often used in scenarios such as beam scanning, missile conformal environment and large beam declination, so this article is a meaningful reference for the selection of the traveling-wave slot array.

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