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Research Article

Substrate Integrated Slot Array Antenna with Required Radiation Pattern Envelope

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A substrate integrated slot array antenna with a prescribed radiation pattern is investigated in this paper. To meet the requirement of a certain standard radiation pattern envelope, the array configuration and the element excitation coefficient should be considered together. An efficient and systematic method is proposed to determine the element number and element weights in a planar array. After that, the geometrical dimension of the substrate integrated slot array can be synthesized. As an example, a K-band 16×22 slot array antenna based on the substrate integrated waveguide (SIW) technology is designed, fabricated, and measured. Its radiation pattern can meet the class 3 antenna radiation pattern envelope of the European Telecommunications Standards Institute (ETSI) standard pattern. Experimental results are in good agreement with simulated ones.

1. Introduction

Substrate integrated waveguide (SIW) antennas have advantages of low loss, low profile, and ease of integration with other planar circuits [1–9]. In practice, it is often necessary to design an antenna array that will yield a desired pattern shape. A very common request is to design an SIW array antenna, whose far-field pattern exhibits low sidelobes [10–17]. These designs only consider how to lower the sidelobe level (SLL) but do not consider how to conform to a desired radiation pattern envelope. Shaped beam is important and essential for an antenna array. For example, an antenna array applied in the European microwave point-to-point communication system should meet the standardized radiation pattern envelope, which is defined by the European Telecommunications Standards Institute (ETSI) [18].

It could be difficult to achieve the ETSI standardized radiation pattern if a conventional low SLL synthesis method is used. To synthesize an SIW antenna array with the desired radiation pattern envelope and gain, the antenna array configuration and the element excitation coefficient should be considered together. On one hand, the array gain depends on the array configuration, the element weights, and the array efficiency. On the other hand, except the element weights, the realizable radiation pattern shape is also determined by the array configuration, that is, the element number and spacing. Thus, an efficient and systematic method is introduced in this paper to provide a fast and accurate solution for this problem.

To validate the correctness of the proposed method, a K-band SIW longitudinal slot array antenna with a proper feeding structure is synthesized to meet the class 3 antenna radiation pattern envelope (20~24 GHz) of the ETSI standard document. It is fabricated and experimented.

2. Design of an SIW Slot Array with Desired Radiation Pattern Envelope

In this section, the design procedure for an SIW slot array antenna is introduced to achieve a desired radiation pattern envelope. A design flow diagram is presented in Figure 1.

Firstly, the SIW dimension is determined. a represents the SIW width, s represents the spacing between adjacent metallic posts, and d represents the metallic post diameter. Generally speaking, the element spacing is a in E-plane. The SIW equivalent width, w_{rwg}, can be calculated by [19]

$$w_{rwg} = a - s\left(0.766e^{0.4482d/s} - 1.176e^{-1.214d/s}\right). \quad (1)$$

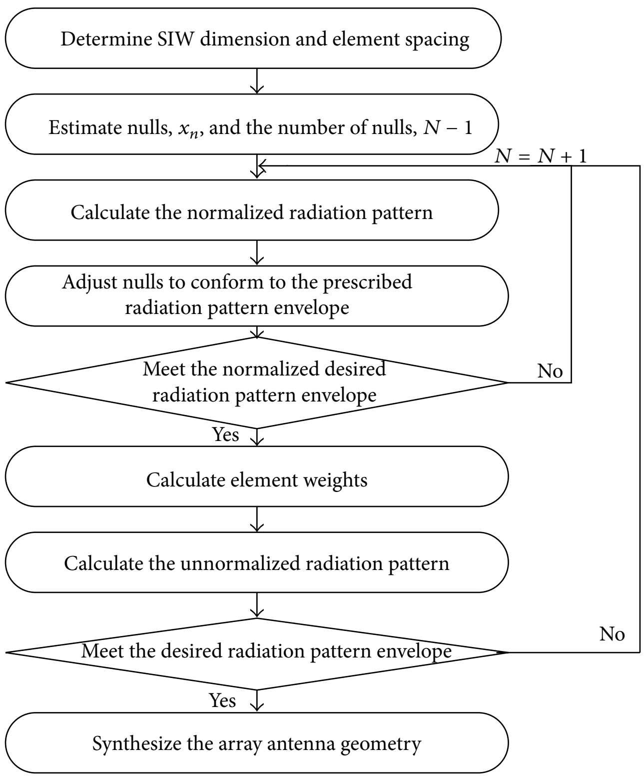

Figure 1: Design flow diagram for an SIW slot array antenna with a desired radiation pattern envelope.

Thus, the guide wavelength, λ_g, can be calculated by

$$\lambda_g = \frac{2w_{rwg}}{\sqrt{\left(2w_{rwg} f_0 \sqrt{\varepsilon_r}/c_0\right)^2 - 1}}. \quad (2)$$

In (2), f_0 represents the center frequency, ε_r is the dielectric permittivity, and c_0 is the light speed in vacuum. In order to locate slots at standing wave peaks, the slot spacing of such an array in H-plane is often chosen as half of the guide wavelength at the center frequency.

When the radiation pattern is synthesized to be below a prescribed radiation pattern envelope, the array configuration and the element weights should be considered together. To simplify the synthesis, the isotropic element is used in this stage. The synthesis of a two-dimensional array antenna can be treated in two parts composed of equal-spacing linear synthesis problems for the principal planes, that is, E-plane and H-plane, respectively.

The array radiation pattern, with respect to the gain at the starting angle of azimuth relative to main beam axis, can be transformed to a polynomial function as follows. In the ETSI standard, the starting angle of azimuth is usually 5°:

$$f(x) = \begin{cases} \prod_{n=1}^{M} \left(\dfrac{x^2 - x_n^2}{x_g^2 - x_n^2} \right), & N = 2M + 1 \\ \dfrac{x}{x_g} \prod_{n=1}^{M-1} \left(\dfrac{x^2 - x_n^2}{x_g^2 - x_n^2} \right), & N = 2M. \end{cases} \quad (3)$$

In (3), N represents the element number, x_n represents the location of the nulls, and x_g represents the location of the normalized point

$$x = \cos\left(\frac{\beta e_s}{2} \cos(\theta) \right). \quad (4)$$

In (4), e_s represents the element spacing. The initial location of the nulls can be estimated by

$$x_n = \cos\left(\frac{n\pi}{N} \right), \quad 1 \le n < \frac{N}{2}. \quad (5)$$

In (5),

$$N > \frac{\lambda_0}{e_s} \sqrt{\frac{G_R}{4\pi}}. \quad (6)$$

In (6), G_R represents the array gain.

Then, the location of the nulls is adjusted to make (3) conform to the prescribed radiation pattern envelope, which is also normalized with respect to the gain at the starting angle of azimuth. The furthest sidelobe is controlled by the minimal x_n. When the furthest sidelobe decreases below the envelope, the next null x_{n-1} is adjusted to control the next sidelobe. At last, the first sidelobe is made below the normalized ETSI radiation pattern envelope. Once the main beam cannot satisfy the required pattern at the current order, the number of nulls should be added for the polynomial function. If the shaped pattern is implemented, the element weights can be obtained by the coefficient of

$$f(z) = \begin{cases} \prod_{n=1}^{M} \left(z^2 + \left(2 - 4x_n^2\right) z + 1 \right), & N = 2M + 1 \\ (z+1) \prod_{n=1}^{M-1} \left(z^2 + \left(2 - 4x_n^2\right) z + 1 \right), & N = 2M. \end{cases} \quad (7)$$

When the element weights in two linear arrays are obtained, the planar array element weights are equal to the product of two linear array weights. In this case, the array aperture efficiency can be estimated by [20]

$$\eta_a = \frac{\left\| \sum_{m,n=1}^{E_{\mathrm{EN}}, H_{\mathrm{EN}}} I_{mn} \right\|^2}{E_{\mathrm{EN}} H_{\mathrm{EN}} \sum_{m,n=1}^{M,N} \left\| I_{mn} \right\|^2}. \quad (8)$$

In (8), E_{EN} is the element number in E-plane, and H_{EN} is the element number in H-plane. I_{mn} is the array element weight. Then, the array realized gain can be estimated by

$$G = \eta_f \eta_a \frac{4\pi E_{\mathrm{EN}} H_{\mathrm{EN}} a \lambda_g}{\lambda_0^2}. \quad (9)$$

In (9), η_f represents the feeding efficiency. Here, it is set as 1 to have sufficient design margin. By use of G, the calculated array radiation pattern based on (3) can be unnormalized and then compared with the desired radiation pattern envelope

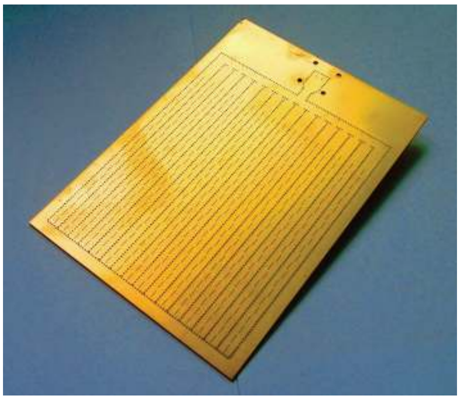

Figure 2: Photograph of the fabricated 16 × 22 SIW slot array antenna.

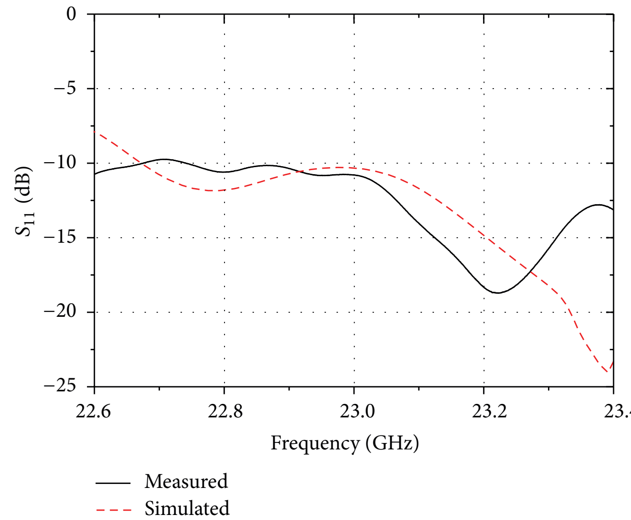

Figure 3: Reflection coefficients of the fabricated 16 × 22 SIW slot array antenna.

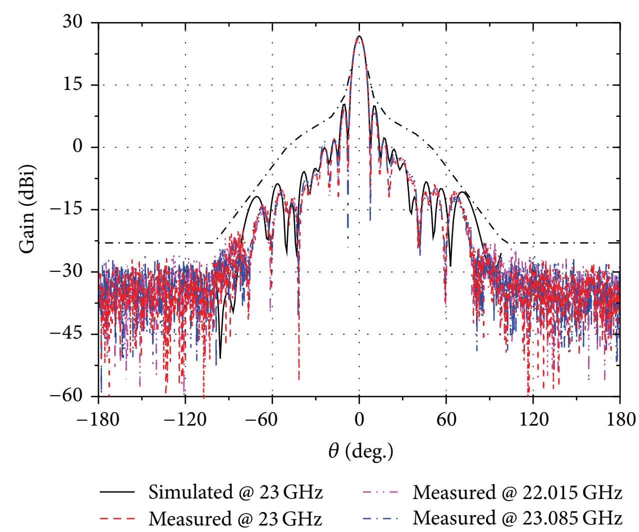

Figure 4: Simulated and measured patterns in E-plane of the fabricated 16 × 22 SIW slot array antenna.

again. If it does not meet the ETSI standard pattern, the polynomial function will be adjusted and be synthesized again.

According to the above discussion, each slot weight has been known. Then, initial parameters of each slot can be synthesized through Elliott's iterative procedure [21] or the method of moment [22]. In this work, the slot length and the offset can be adjusted, and the slot width keeps unchanged. At last, the planar array antenna is modeled in HFSS and full-wave optimized.

3. Design Results

As an example, a 16 × 22 slot array antenna is designed to meet the class 3 antenna radiation pattern envelope (20~24 GHz) of the ETSI standard pattern. It is designed based on the Taconic TLY-5 substrate with a thickness of 1.52 mm. The permittivity and loss tangent of the substrate are 2.2 and 0.0009, respectively. This design includes a 1-to-16 alternating phase power divider and a waveguide-to-SIW transition. The antenna works at the center frequency of 23 GHz. The SIW width is 7.2 mm, the spacing between adjacent metallic posts is 1.5 mm, and the metallic post diameter is 0.8 mm.

The designed SIW slot array antenna is fabricated as shown in Figure 2. Its reflection coefficient is measured by a vector network analyser. The measured result compared with the simulated one is presented in Figure 3. The −10 dB reflection coefficient bandwidth is more than 700 MHz.

The copolarized and cross-polarized radiation patterns in E-plane and H-plane of the array antenna are measured in a microwave anechoic chamber. As shown in Figures 4 and 5, patterns within the desired frequency band are all below the ETSI pattern envelope. Besides, the tested antenna gain is 26.77 dBi, 27.28 dBi, and 26.78 dBi at 22.015 GHz, 23 GHz and 23.085 GHz, respectively. It can be seen that the measured antenna gain is more than 26.0 dBi within the frequency range of 170 MHz. The radiation efficiency is 74.3% at the center frequency.

4. Conclusion

In this paper, a systemic method is proposed to design a substrate integrated slot array antenna with the required antennas radiation pattern envelope. To validate the correctness of our design, an SIW slot array antenna with the class 3 radiation pattern envelope (20~24 GHz) of the ETSI standard pattern is fabricated and measured. Measured results are in good agreement with simulated ones. It conforms to the ETSI standard document and the array antenna gain is more than 26 dBi within the whole interested frequency range.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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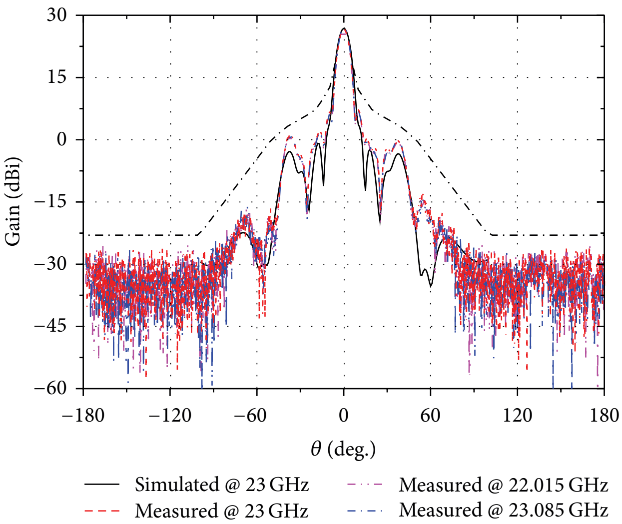

FIGURE 5: Simulated and measured patterns in H-plane of the fabricated 16×22 SIW slot array antenna.

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