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Research Article

Design of a Compact Broadband 90° Waveguide Twist Based on Double-Corner-Cut Square Slots

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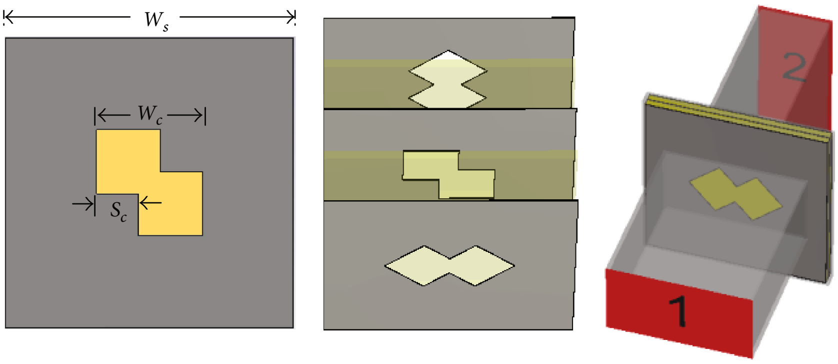
A new compact broadband waveguide twist by double-corner-cut square slots is presented. In particular, the proposed module is made from two substrate layers and three copper cladding layers, which can be used as the waveguide twist and broadband filter. A double-corner-cut square slot is etched on each metal layer with relative rotation. It is found that the optimized module can provide the bandwidths of no less than 6.1% at the 10-dB return-loss level or 4.3% at the 20-dB level with a minimum length of 0.07 waveguide width.

1. Introduction

Waveguide twists are often necessary to provide polarization rotation between waveguide-based components. They are also commonly assigned before the antenna in order to change the antenna polarization. Commercially available twists adopt a continuous rotation, but they are not suited for integrated applications because of their large dimensions. The typical length of commercially available 90° continuous twists can be fivefold of the waveguide width to guarantee the standing wave ratio (SWR) of less than 1.1 over the full waveguide band [1]. Also, their rigorous curve structure makes them difficult and costly in manufacturing. In order to decrease the twists' volume and longitudinal length, step twisting of waveguides is well documented in literature [2–6]. In [4], a circular waveguide is inserted into two adjacent steps to improve impedance bandwidth. Multiple rectangular steps are used to achieve arbitrary polarization rotation in [7–10]. The step twists presented in [7] can provide a 40-dB return-loss level bandwidth of 40% with its longitudinal length equal to 1.86 waveguide width. A single step twist consists of double-corner-cut square waveguide in [11] can form extremely short twists (about 0.296 waveguide width) while showing relatively broad bandwidth (31% at the 30-dB return-loss level). The double-corner-cut square configuration is introduced in our waveguide twist design.

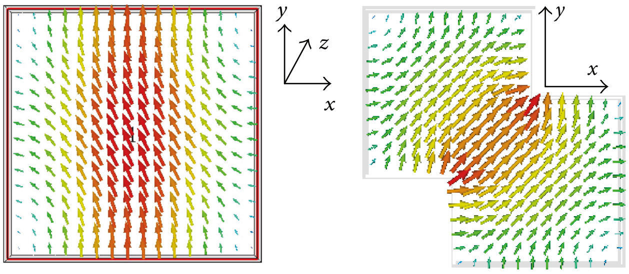
For example, by inserting dielectric substrate into a horn antenna for the purpose of realizing notch filter [12, 13] and metal sheet achieving rectangular to circular waveguide transfer [14], Barbuto et al. made a dielectric-based extremely short (about 0.106 waveguide width) waveguide twist in [15]. Dielectric substrate can further reduce the twists' longitudinal length; also, their machine can take standard PCB, which would decrease their cost and weight effectively. However, their impedance bandwidth can be relatively narrow because of using inductively loaded slotted rings. This makes them hard to be used in many communication scenes (especially in satellite communication scenes that have strict demands on speed and message capacity).

This paper presents a compact broadband 90° waveguide twist based on dielectric substrate. Compared to the dielectric-based waveguide twist reported in [15], whose configuration is induction-loaded slotted rings, the double-corner-cut square slots' configuration presented in this paper has broader bandwidth and more compact size. In particular, the 10-dB return-loss level increases from 1.52% to 6.1%, the 20-dB return-loss level increases from 0.24% to 4.3%, while the longitudinal length of the twist decreases from 0.106 waveguide width to 0.07 waveguide width.



(a) (b) (c)

Figure 1: The proposed 90° waveguide twist. (a) Middle cladding layer with double-corner-cut square. (b) Three cladding layers with rotational double-corner-cut squares and two substrate layers. (c) Whole structure sketch.



(a) (b)

Figure 2: The electrical field pattern of the infinite double-corner-cut waveguide. (a) Without the corner cut. (b) With the corner cut (mode TE_{1m}).

2. Overview of the Proposed Structure and Their Working Modes

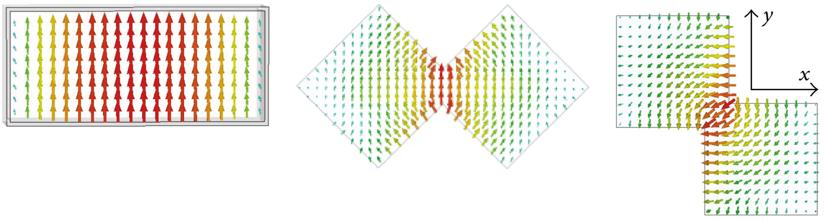
The proposed 90° waveguide twist is shown in Figure 1. The key parameters are as follows: substrate square width $W_s = 26.8$ mm, slot square width $W_c = 9.1$ mm, and double-corner-cut square width $S_c = 4$ mm. The two corner-cut squares are imposed on the diagonal line of the slot square as shown in Figure 1(a). In particular, the proposed module consists of two double-sided copper-clad laminate sheets (F4B with thickness of 0.8 mm and dielectric constant $\varepsilon_r = 2.55$), where three double-corner-cut, properly rotated squares are etched, as shown in Figure 1(b). Then, the proposed module is inserted between two connected and mutually orthogonal WR-90 waveguide sections, as shown in Figure 1(c). The rotation angle of the squares are −45°, 0°, and 45°, respectively.

With no corner cut, the square waveguide has two dominant degenerate modes, TE_{10} and TE_{01} modes. They own the same resonant frequencies and perpendicular electric field distributions and are decoupled from each other.

With the corner cut, the two dominant modes will be coupled with each other, and the resonant frequencies will split. As a comparison, the electric field distribution with and without the corner cut is shown in Figure 2.

As described in [16], the working modes of this corner-cut waveguide are still TE and TM modes. Their electrical field can be treated as a perturbed difference and sum combination of the TE_{10} and TE_{01} mode fields which have equal magnitude and electric components, respectively [17]. These perturbed modes, which are named TE_{1e} and TE_{1m}, result in the electrical field distributions to be parallel or perpendicular to the plane passing through the corner vertices. What is more, the variation of the cutoff frequency parameters with the normalized cut size and the module's broadband performance in a double-corner-cut square waveguide are discussed in detail in [11]. Hence, we introduce the double-corner-cut square configuration as our dielectric-based waveguide twist in order to achieve a broadband performance.

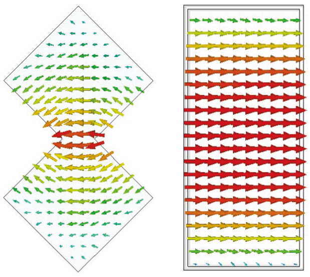
The electrical field distributions of the optimized module on different cross-sections at frequency 11.3 GHz are shown in Figure 3. It can be seen from Figures 3(a) and 3(e) that their working modes are TE_{10} and TE_{01} in the assigned coordinate system shown in Figure 3(c), respectively. The electrical field distributions on the rotational cladding cross-sections are very much similar to the TE_{1m} mode, which gradually changes the field direction from vertical to horizontal. Due to the broadband performance of this double-corner-cut square reported in [11], the optimized module here working at the same modes



(a) Cross-section of the horizontal waveguide

(b) Cross-section of the first cladding with −45° rotating angle

(c) Cross-section of the second cladding with 0° rotating angle



(d) Cross-section of the third cladding with 45° rotating angle

(e) Cross-section of the vertical waveguide

Figure 3: The electrical field pattern of the infinite double-corner-cut waveguide (mode TE_{1m}).

also owns relative broadband performance. The difference between the proposed module and the one reported in reference [11] is their thickness. In [11], the thickness of the module reaches 0.37 waveguide width and the change of thickness will change the resonant frequency as the twist is regarded as a resonant cavity. In our proposed module, two substrate layers are used instead. The thickness of the resonant cavity can be reduced effectively for the use of the substrate.

3. Simulated and Tested Results

The proposed 90° waveguide twist is simulated by the finite-difference time-domain (FDTD) method in CST studio. The optimized S parameters with and without the waveguide twist are shown in Figure 4. It can be seen that two directly connected and mutually orthogonal WR-90 waveguide without twist have a very high return-loss level, which means that nearly all the microwave energy are reflected. When the optimized twist is assigned, it can provide the bandwidth of 6.1% (11.05–11.72 GHz) at the 10-dB return-loss level or 4.37% (11.19–11.69 GHz) at the 20-dB level. Compared to the impedance bandwidth given in [15], both the 10-dB and 20-dB return-loss level bandwidths improve effectively. The longitudinal length of the twist also decreases from 0.106 to 0.07 waveguide width.

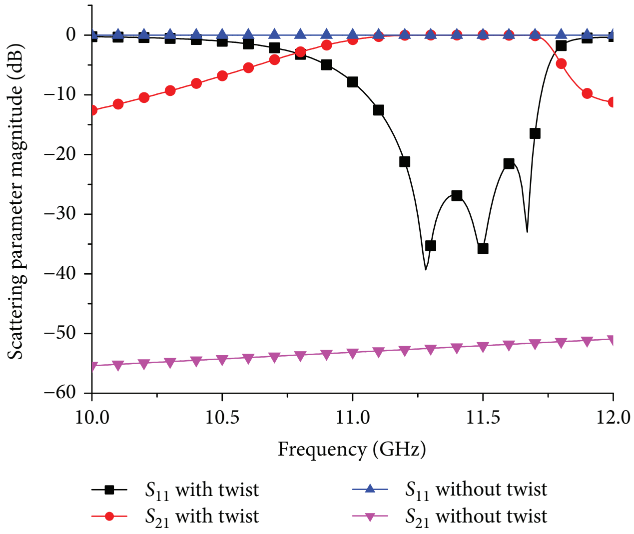


Figure 4: The optimized S parameters with and without the waveguide twist.

The study of the scattering parameters versus frequency with variable W_s, W_c, and S_c is shown in Figures 5, 6, and 7, respectively. In Figure 5, it can be pointed out that, as the side length of the substrate square W_s increases, the resonant frequency decreases due to the increase of the square waveguide cavity. In Figure 6, it is shown that the resonant frequency increases with the increase of the slot square width W_c. The square waveguide cavity becomes smaller as W_c increases; thus, the resonant frequency increases as presented in Figure 5. In Figure 7, it is shown that, with the increase of the double-corner-cut square width S_c, the resonant frequency decreases, too. When $S_c = 4.1$ mm, three nearby resonant frequencies appear, which would increase the bandwidth of the waveguide twist effectively. Optimized parameters are shown as follows: the substrate square width

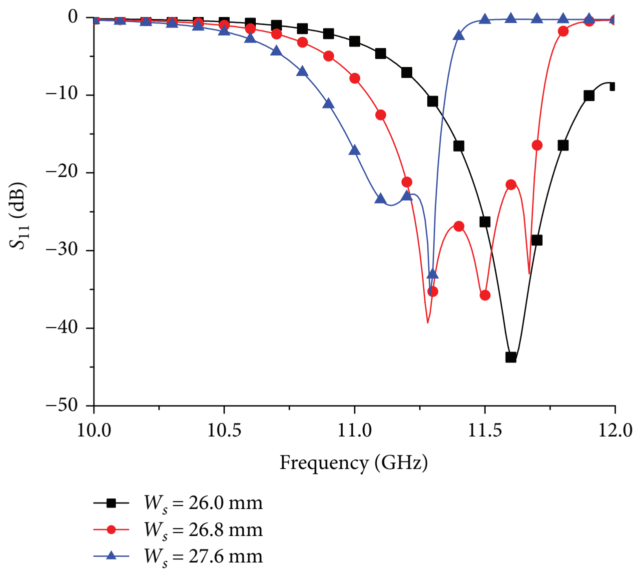


FIGURE 5: The scattering parameters versus frequency with variable W_s ($W_c = 9.1$ mm, $S_c = 4$ mm).

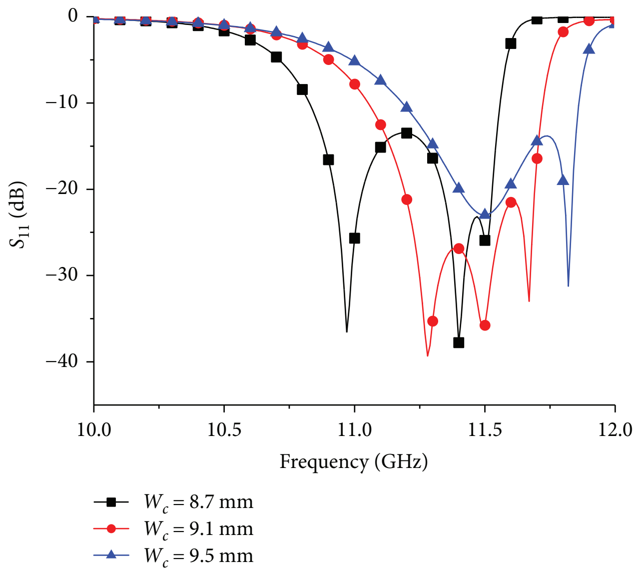


FIGURE 6: The scattering parameters versus frequency with variable W_c ($W_s = 26.8$ mm, $S_c = 4$ mm).

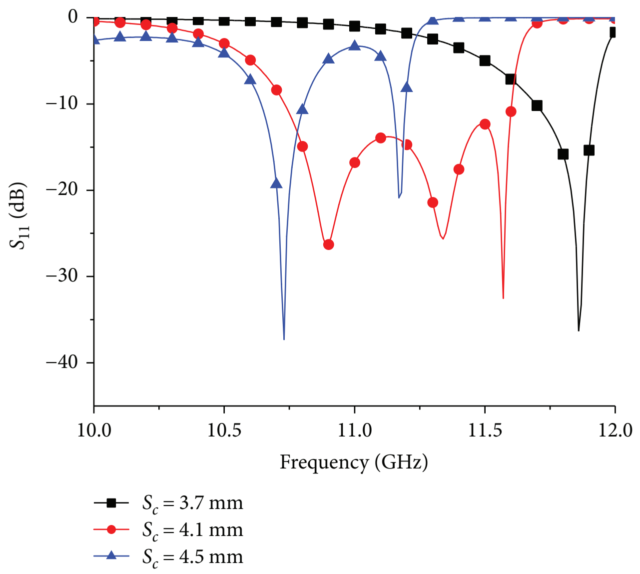


FIGURE 7: The scattering parameters versus frequency with variable S_c ($W_s = 26.8$ mm, $W_c = 9.1$ mm).

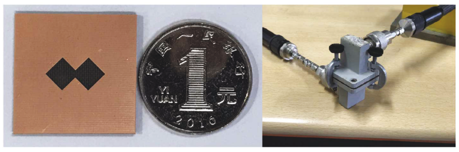


FIGURE 8: Photograph of the experimental waveguide twist and the proposed waveguide twist assigned between two mutually orthogonal waveguides.

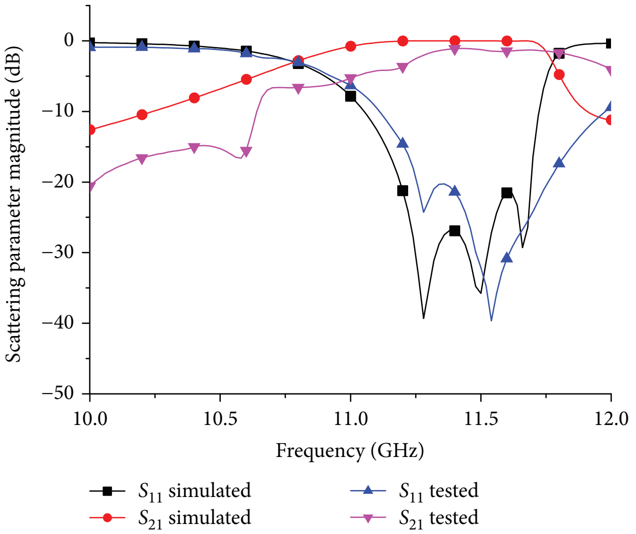


FIGURE 9: Simulated and tested scattering parameter magnitudes.

$W_s = 26.8$ mm, the slot square width $W_c = 9.1$ mm, and the double-corner-cut square width $S_c = 4$ mm.

The experimental waveguide twist with the optimized parameters is shown in Figure 8. The proposed waveguide twist assigned between two mutually orthogonal waveguides is also shown in Figure 8. The measurement is achieved by an Agilent N5244A PNA-X network analyzer. Two WR-90 waveguides are assigned which are mutually orthogonal to each other, and the proposed waveguide twist is directly inserted between the two waveguides as shown in Figure 8. The simulated and tested scattering parameter magnitudes are shown in Figure 9. Comparing the simulated and tested S_{11}, the latter results have some frequency shifts and amplitude decline, which may have been caused by fabrication and testing error. It can be seen from Figure 9 that the tested S_{11} only owns two resonant frequencies. The highest

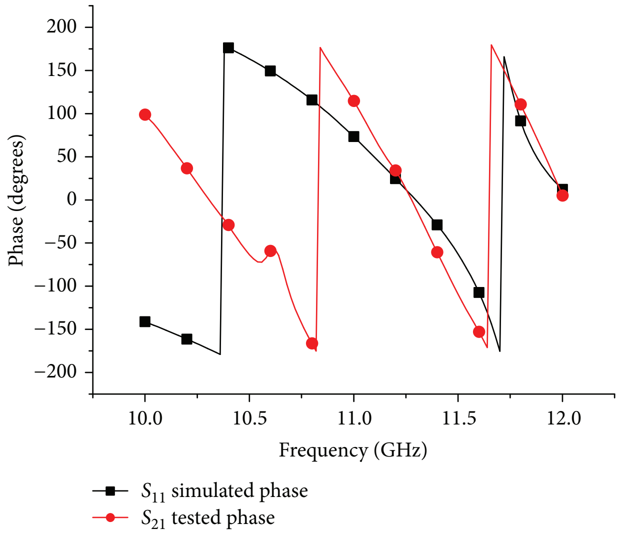


Figure 10: Simulated and tested scattering parameter magnitudes.

resonant frequency is missed when compared to the simulated one, which is caused by the assembly error. The tested results may be a little large, especially when the waveguide twist is assembled by ourselves.

In addition, the simulated and tested phase curves of S_{21} are shown in Figure 10. They match well near the resonant frequency, both the linear changes and frequency, which means a small phase distortion in communication. This characteristic makes it suitable in filter applications.

4. Conclusion

A compact broadband 90° waveguide twist based on double-corner-cut square slots is presented in this letter. The optimized module can provide the bandwidths of no less than 6.1% at the 10-dB return-loss level or 4.3% at the 20-dB level with a minimum length of 0.07 waveguide width. Both the bandwidth and thickness improve a lot when compared to the firstly introduced dielectric-based waveguide twist reported in [15]. In particular, the 10-dB return-loss level increases from 1.52% to 6.1%, the 20-dB return-loss level increases from 0.24% to 4.3%, while the thickness of the twist decreases from 0.106 to 0.07 waveguide width. To the best of the authors' knowledge, the proposed module may be the shortest waveguide twist ever presented in the current literature. In addition, the simulated and tested phase curves of S_{21} match well near the resonant frequency, both linear changes and frequency, which means a small phase distortion in communication. These characteristics make them suitable in compact communication scenes and in some filter applications.

Conflicts of Interest

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

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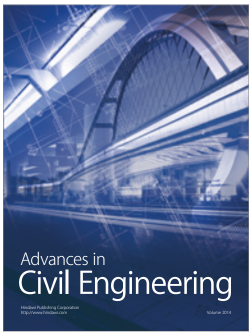

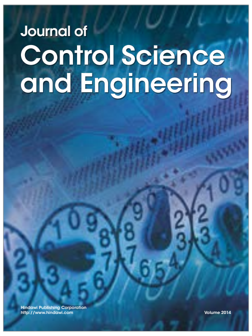

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