Short-Range Transmission Improvement by Dog-Bone Cross-Slot Feed in Radial Line Slot Antenna

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Abstract: A radial line slot antenna (RLSA) was proposed as a candidate for short-range transmission. The introduction of the dog-bone cross-slot feed improves the field distribution of the rotating mode excited in the radial waveguide. The method of the dog-bone cross-slot based on eigenmode analysis is presented to radiate the rotating mode at the design frequency. The short-range transmission improvement between two antennas is demonstrated experimentally.

Keywords: radial line slot antenna, dog-bone, short-range transmission

Classification: Antennas and propagation

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1 Introduction

The radial line slot antenna (RLSA) was originally proposed for satellite broadcast reception [1]. The RLSA was also proposed for short-range transmission such as wireless power transfer [2]. A slot antenna [3] is used to feed a waveguide instead of a coaxial-line for a high-power transfer such as wireless power transfer [4]. For a concentric-array RLSA, a cross straight-slot feed was introduced [2]. This introduction of a dog-bone cross-slot was to reduce the amplitude ripples in the $\phi$ direction in the radial waveguide for enhancing the aperture efficiency [5] since the dog-bone slot antenna [6] can be shortened by the dog-bone shape with keeping the resonant frequency in comparison with the straight-slot antenna.

This manuscript proposes to design the dog-bone cross-slot to feed a radial line based on the eigenmode analysis and confirms the improvement of the short-range transmission between two concentric-array RLSAs. The eigenmode analysis for an antenna including its circumference is applied to know the complex resonant frequency of the antenna. The ratio of the imaginary part over the real part of the obtained complex resonant frequency is relating to the quality factor or the bandwidth of the antenna. The eigenmode analysis is applied to a dog-bone cross slot on a shorted rectangular waveguide, where a complex-value eigenfunction corresponding to the rotating mode is achieved. We also demonstrate that the adoption of the dog-bone cross slot in the RLSA improves the short-range transmission in comparison with the straight cross-slot.

2 Design

The proposed RLSA is composed of two parts: 1) the feeding part in the lower layer 2) the radiating part in the upper layer, as shown in Fig. 1. The feeding part is composed of an air-filled rectangular feeding waveguide and an air-filled dog-bone cross slot. The radiating part is composed of a poly tetra fluoro ethylene (PTFE)-filled radial waveguide and an array of radiating slot pairs. PTFE has a dielectric constant of 2.16 and a loss tangent of 0.001. The feeding waveguide, dog-bone cross slot, and radial waveguide are of aluminum with bulk conductivity of $3.8 \times 10^7$ S/m and the radiating slots are of copper with bulk conductivity of $5.8 \times 10^7$ S/m. These dielectric constant and conductivity are used in the analysis. We focus mainly on the design of the dog-bone cross-slot based on eigenmode analysis. The dimensions of a dog-bone cross slot are analyzed using HFSS eigenmode analysis to radiate the rotating mode at the design frequency of 5.80 GHz. The full antenna structure is designed for matching and excitation using HFSS.

We start the analysis with the initial model shown on the left side of Fig. 2 (a); a dog-bone single-slot over a rectangular cavity with prefect electric conductors (PEC) in their walls and an infinite parallel plate waveguide over the dog-bone single-slot (a rectangular terminated by impedance boundaries since all the power to the parallel plate waveguide will be designed to radiate by the radiating slot pairs). The initial dimension of the dog-bone single-slot is determined in [5]. By properly scaling the length of the dog-bone single-slot (while keeping the ratio between the length of the center part of the dog-bone single-slot and the length of the edge parts [5]), the resonant frequency can be controlled.
A dog-bone cross slot will be created by combining two dog-bone slots perpendicularly. The length of one slot should be shorter and the length of the other slot should be longer than the resonant length at the design frequency to excite rotating modes.

The right side of Fig. 2 (a) shows the model of a dog-bone cross slot by combining two dog-bone slots on the PEC-wall rectangular cavity. The distance from the slot to the right PEC-wall of the rectangular cavity are set to be a quarter guided wavelength to include the effect of the PEC-wall to the slot in the actual antenna. The distance from the slot to the left PEC-wall of the rectangular cavity are set to be a half guided wavelength, so that the resonance of the rectangular cavity should be avoided to achieve only the resonance of the slot. In this model, the dog-bone cross slot has two resonant frequencies at 5.68 GHz and 6.05 GHz with the quality factors of 15.23 and 19.26, respectively. The eigenmode is typically a real-value function in a loss-less case. That at the resonant frequency of 6.05 GHz is demonstrated in the left side of Fig. 2 (b). It has an eight-shaped pattern, which means only the shorter dog-bone slot is excited because the mutual coupling between the two dog-bone slots is negligibly small.

We apply an impedance boundary equal to the wave impedance of TE10 mode of the feeding waveguide in the eigenmode analysis as indicated on the right side of Fig. 2 (a). The propagation from the dog-bone cross slot to the feeding and parallel plate waveguides is reciprocal to the propagation from the feeding and parallel waveguides to the dog-bone cross slot. As a result, the eigenmode becomes a complex-valued function, so the rotating mode is observed in the radial waveguide at 6.05 GHz (the resonant frequency) on the right side of Fig. 2 (b). Finally, the overall size of the dog-bone cross slot needs to be adjusted (scaled) so that the operating frequency is shifted to 5.8 GHz. We adjust the angle of the dog-bone cross-slot to minimize the amplitude ripples of E-field in the φ direction in the parallel plate (radial) waveguide. The reflection is minimized by adjusting the distance between the dog-bone cross-slot and the shorted end of the feeding waveguide. Almost all the adjustments of the parameters are done by the eigenmode analysis while only the small adjustments on the circumferential amplitude ripples and the reflection are done by the excitation analysis.

The parameters of the dog-bone cross-slot are given as follows; the length of the center parts is 10.40 mm and 9.18 mm, the length of the edge parts is 3.88 mm and 3.42 mm, the angle of the slot is 48 deg., and the slot thickness is 1.50 mm. The distance to the short end of the feeding waveguide is 25.75 mm (approximately a quarter of the feeding guided wavelength).

The overall structure as shown in Fig. 1 is the combination of the designed feeding part and the radiating part. The design of the radiating part is detailed in [5]. The reflection is below -25 dB at the design frequency. The bandwidth for the reflection below -15 dB is approximately 5% of the center frequency.
Fig. 1 Antenna structure

Fig. 2 (a) Dog-bone cross-slot model for eigenmode analysis

Amplitude Distribution

Phase Distribution
3 Measured Results

Fig. 3 (a) shows the simulated relative amplitudes of the electric field inside the radial waveguide at the radius of 175 mm (five times of the wavelength inside the radiating waveguide) from the center of the dog-bone cross-slot. The amplitude ripple fed by the dog-bone cross-slot (1.8 dB) is smaller than that fed by the straight cross-slot (2.5 dB). The introduction of the dog-bone cross-slot improves the rotating mode inside the radial waveguide, which can enhance the uniformity of the aperture field distribution.

We discuss short-range transmission in which two antennas are identical and their centers coincide. Fig. 3 (b) shows the measured transmissions between the two antennas for a range from 50 mm to 100 mm. The period of the distance dependence of the transmission is about 25 mm which is a half free-space wavelength. The ripples come from multiple reflections between the two antennas. The improvement of the uniformity in the aperture field distribution is reflected. The antenna using the dog-bone cross-slot (red line) has smaller amplitude ripples (3.2 dB) and a higher transmission level by 1.0 dB than that using the straight cross-slot (blue line). These differences gradually disappear over the distance because at larger distances the contribution of the field uniformity becomes smaller as the result of the beam divergence. The measured reflection is demonstrated in Fig. 3 (c). That for the dog-bone cross-slot antenna is large (about -5 dB) at the distances around 55 mm and 80 mm, where the transmission for the dog-bone cross-slot-fed antenna is smaller than that for the straight cross-slot-fed antenna. The reflection of the dog-bone cross-slot-fed antenna should be suppressed as a future study.
Fig. 3 (b) Measured transmissions for a distance range from 50 mm to 100 mm

Fig. 3 (c) Measured reflections for a distance range from 50 mm to 100 mm

4 Conclusion
The eigenmode of the dog-bone cross slot in the RLSA has been analyzed. The adoption of the dog-bone cross-slot feed has improved the short-range transmission between the two antennas, which means the ripples in the distance dependence of the transmission is reduced compared to the conventional straight cross-slot feed.