Wideband waveguide antenna using stepped L-shaped probe for wide-angle circular polarization radiation

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Abstract: A circularly polarized (CP) waveguide antenna using L-shaped probe is presented. The proposed antenna can cover the UWB (Ultra Wideband) high-band (34.3%: 7.25 GHz–10.25 GHz in Japan) with 3-dB axial ratio (AR) having a wide range of angle in the radiation patterns. For obtaining this performance, a stepped structure is introduced in the L-shaped probe. The optimization of the stepped structure can control the amplitude ratio of the two orthogonal modes of electric field. This can enhance the AR bandwidth of the previously proposed waveguide antenna using an L-shaped probe and parabolic short wall. Finally, the proposed structure achieves 39% of 3-dB bandwidth keeping a wide angle for radiating CP in an angle of around 135°.

Keywords: circular polarization, wideband antenna, waveguide antenna, L-shaped probe, axial ratio

Classification: Antennas and Propagation

References

[1] S. L. S. Yang, A. A. Kishk, and K. F. Lee, “Wideband circularly polarized antenna with L-shaped slot,” IEEE Trans. Antennas Propag., vol. 56, no. 6, pp. 1780–1783, June 2008. DOI:10.1109/TAP.2008.923340
[2] J. S. Row and S. W. Wu, “Circulary-polarized wide slot antenna loaded with a parasitic patch,” IEEE Trans. Antennas Propag., vol. 56, no. 9, pp. 2826–2832, Sept. 2008. DOI:10.1109/TAP.2008.928769
[3] T. Fukusako, N. Noguchi, and S. Yamaura, “Bandwidth enhancement of circular polarization generated from circular waveguide and L-shaped probe,” 2013 IEEE International Workshop on Electromagnetic (iWEM2013), Hong Kong, China, pp. 5–8, Aug. 2013. DOI:10.1109/iWEM.2013.6888755
[4] S. Yamaura and T. Fukusako, “Reduction of cross polarization in higher frequency for circularly polarized broadband antenna with L-shaped probe and parabolic short wall,” IEICE Commun. Express, vol. 2, no. 5, pp. 180–185, May 2013. DOI:10.1587/comex.2.180
[5] R. Yamauchi and T. Fukusako, “A broadband circularly polarized waveguide antenna design for low cross-polarization,” IEICE Trans. Commun., vol. E99-B, no. 10, pp. 2187–2194, Oct. 2016. DOI:10.1587/transcom.2015EBP3544
[6] T. Fukusako and R. Yamauchi, “Broadband waveguide antenna using L-shaped
Circularly polarized (CP) antennas have advantages, such as reducing effects of multipath fading and no need of considering antenna alignment. This is because the amplitude of electric field is constant at any angle in the wave front, and the sense of CP is switched from left-hand (LH) CP to right-hand (RH) CP and vice versa as long as the incident angle is less than the Brewster angle. To make the maximum use of such advantages, the cross-polarization (XPOL) should be reduced to decrease the AR.

Furthermore, broadband antennas are required to increase channel capacity in wireless telecommunications. Some CP waveguide antennas using L-shaped probes have been recently reported [1, 2, 3, 4, 5, 6]. The L-shaped probe is bent at a bending point to make the 90-degree phase difference between the two orthogonal modes. However, its asymmetrical structure easily generates XPOL in the off-boresight directions. In order to reduce the XPOL to widen the angle for radiating CP, a waveguide CP antenna with a parabolic shorting wall [4] was proposed. To reduce the AR in this structure, a narrowed aperture has been also proposed in [5]. This structure has low AR (<1 dB) and wide angle for CP, however the 3-dB AR bandwidth is narrower than UWB highband and the AR bandwidth of previous structures [4]. This letter presents that an optimized stepped structure of the L-shaped probe is effective to obtain a wideband AR characteristics for UWB High-band in the waveguide antenna keeping sufficient low XPOL in off-boresight directions.

2 Antenna structures and characteristics

Fig. 1 shows the proposed antenna structure with a narrowed aperture and a parabolic wall as a short wall. For this antenna, the feeding L-shaped probe has a stepped structure in the probe structure with a size of the narrower part of $K$. In addition to this, $R$ is the diameter of the thick part of probe. Furthermore, a stepped aperture is introduced in order to reduce higher order modes [3]. The proposed antenna is fed through an inductive coaxial structure so as to cancel the capacitive impedance. Considering the required UWB high band from 7.25–10.25 GHz, the
waveguide diameter has been set at 27.0 mm in order to have a cutoff frequency at 6 GHz. For the center frequency at 8.75 GHz, the length between the probe and the tip of the parabolic wall should be around $\lambda_g/4$, where the $\lambda_g$ is the effective wavelength. The length of two sides of the probe should be chosen in order to generate the TE$_{11}$ mode crossing spatially at the right angle having a 90-degree phase difference. The narrowed aperture structure is effective to reduce the AR and widen the angle for CP in the radiation pattern. This design has been discussed in [5].

In addition to this, the propose antenna has three techniques to reduce XPOL in a wideband frequency. At first, a parabolic short wall with $x = 0.8(y^2 + z^2)$ is installed based on the parabolic shorting wall reported in [4]. This reduces XPOL in wide angle ranges in the radiation patterns, because the variation in distance between the bent point of L-shaped probe and shorting wall can be almost constant with respect to any angle centered at a bent point. As the second, the entire length $L$ along $x$ direction is optimized to be chosen at 43.7 mm considering the AR behavior. With a decrease in $L$ from 57.7 mm to 43.7 mm, AR in higher frequency band around 9.40 GHz is gradually reduced with a sinusoidal variation. As the third technique, the narrowed aperture is used, that is, we have made the diameter of aperture $D$ smaller to be 27.6 mm than the inside diameter [5]. The probe structure in Fig. 1(b) is identical with the probe in [5] when $K = 13.5$ mm and $R = 1.0$ mm. However, for $K = 7.5$ mm and $R = 1.8$ mm, $-10$-dB $S_{11}$ bandwidth of 44.6% (6.7–10.6 GHz) is obtained as shown in Fig. 2(a). The bandwidth has been expanded a little compared to that in [5]. AR characteristics is obtained as in Fig. 2(b) with a 3-dB AR ratio of 39% (7.0–10.4 GHz) covering the UWB high band. Choosing the $K$ and $R$ as the above values, the widest AR bandwidth is obtained. Furthermore, Fig. 2(b) also shows gain characteristics along the boresight direction. The gain of the proposed antenna has the close gain characteristics to [5]. The measured gain is slightly lower by 1 dB at most in the higher frequency. This is
mainly due to an uncertainty of the phase center regarding the proposed antenna and the standard antenna, where our standard antenna is available for $\leq 10$ GHz.

Fig. 2(c) shows the variation in amplitude characteristics as a function of $K$ with $R = 1.8$ mm. An increase in $K$ from 4.5 mm to 7.5 mm controls mainly $E_\theta$ in the lower frequency. Furthermore, with an increase in $R$ from 1.2 mm to 1.8 mm, the amplitude of $E_\phi$ increases in the far field as shown in Fig. 2(d). The both

![Graphs showing amplitude characteristics of $E_\theta$ and $E_\phi$](image)

Fig. 2. Antenna performances.
amplitude characteristics are sensitive to $R$ throughout the frequency. As a result, choosing the suitable $K$ and $R$, we can obtain the widest AR bandwidth of 39% (7.0–10.4 GHz) with $R = 1.8$ mm and $K = 7.5$ mm covering the UWB high-band.

3 Radiation patterns

Fig. 2(e) shows radiation patterns at 8 GHz and 9 GHz for both $xy$- and $zx$-planes. The measured results (mea.) shows good agreements with simulated (sim.) results. For 3-dB AR, XPOL should be smaller than co-polarization by more than 15 dB. Considering this, 3-dB AR is obtained covering 150° and 160° in $xy$- and $zx$-planes, respectively, at 8 GHz. At 9 GHz, 135° and 125° are available for CP in $xy$- and $zx$-planes, respectively. Although the bandwidth for 3-dB AR has been expanded, the obtained angles are comparable with those in [5].

4 Comparison of antenna performances

As discussed above, the antenna performance is sensitive to the probe structure. The performance of the discussed structure is compared with some other CP cavity-type or waveguide antennas [5, 7, 8, 9]. However, some have high gain with a horn, and others have low gain. For a comparison with a fair condition, we try discussing the comparison using products of antenna gain $G$ and angle $\theta_c$ (in $xy$-plane for [5] and the proposed structure) in which CP with the 3-dB AR is radiated, as we know empirically that these two parameters have a trade-off relation mutually. The performances of the related antennas are summarized in the Table I, where the frequency is a representative value around the center frequency of operating band, and the ARBW is the 3-dB bandwidth of AR in % at the center frequency of the respective bandwidths.

| Ref. | Freq. [GHz] | ARBW [%] | $G$ [dBiC] | $\theta_c$ [°] | $G\theta_c$ [°] |
|------|-------------|----------|-------------|----------------|----------------|
| [7]  | 20          | -        | 14.5        | 30             | 848.5          |
| [8]  | -           | 35       | 7.8         | 140            | 843.5          |
| [9]  | 2.2         | 26       | 15          | 34             | 1075.2         |
| [5]  | 9.0         | 35       | 9.6         | 146            | 1331.5         |
| Proposed | 9.0     | 39       | 9.3         | 135            | 1149.0         |

In the table, the antenna in [7] is fed with a 2-point feeding structure, and the antenna in [8] is fed with a 4-point feeding structure and have a wider AR bandwidth than [7], however their $G\theta_c$ products are close to each other but no more than 850 degrees. An antenna with a truncated horn antenna and 1-point feeding structure has a higher $G\theta_c$ product [9]. Compared these antennas, the antenna with an L-shaped probe in [5] has a higher $G\theta_c$ product with a wider AR bandwidth which is comparable with the AR in [8] having the 4-point feeding. The proposed antenna has a little bit smaller $G\theta_c$ product than [5], however the proposed antenna can achieve a wider AR bandwidth with a small sacrifice of $G$.
Furthermore, according to the comparison in Fig. 2(b), the proposed antenna has higher ARs but the highest one is still less than 3 dB in the required frequency. From the discussion above, we can choose the better AR or $G\theta_c$ by optimizing the probe structure. As a result, the proposed antenna is the only structure that can cover UWB high band and high $G\theta_c$ product in cavity-type antennas.

5 Conclusion

In this letter, a design technique of the L-shaped probe is presented to improve the AR bandwidth of the waveguide antenna in [5]. The probe design can change the amplitude characteristics of the orthogonal electric field for CP. The proposed probe structure can achieve CP in a wideband frequency range of 39% for covering UWB high-band (7.25–10.25 GHz in Japan) keeping a wide range of angles around 120°–150° in the radiation patterns.

Acknowledgments

This work was supported by the Ministry of Education, Culture, Sports Science and Technology (MEXT) Grant-in-Aid for Scientific Research (C), and the Telecommunication Advancement Foundation.