X-Band Circularly Polarized HMSIW U-Slot Antenna

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Abstract. *In this paper, a circularly polarized U-slot half-mode substrate integrated waveguide (HMSIW) antenna is proposed. It is based on a combination of U-shaped slot etched in the HMSIW top wall and a shorting via placed between the area bounded by the slot and the HMSIW bottom wall. The antenna is designed for the operating frequency of 10 GHz, parametrically studied, fabricated and experimentally verified. Experimental results prove that the fabricated prototype radiates a left handed circularly polarized (LHCP) electromagnetic wave and it achieves the impedance bandwidth of 11.9% for the reflection coefficient less than –10 dB, the axial ratio (AR) bandwidth 2.2% for AR less than 3 dB, and the LHCP peak gain of 6 dBi. The proposed antenna combines attractive features like low profile, low weight and low cost fabrication process.*

Keywords

Slot antenna, HMSIW, circular polarization

1. Introduction

Circularly polarized antennas are widely used to solve problems of polarization mismatch and multipath interference in satellites and radar applications. It is usually desirable that such antennas should be low cost, low profile, light weight and have good impedance matching and radiation performance. An appropriate candidate for such an antenna can be an antenna [1–6] based on the substrate integrated waveguide (SIW) technology [7]. However, for some applications especially at lower frequencies, the width of SIW can be too big. Thus, the reduction of the SIW size is a very desirable task. The most feasible solution is to exploit a half-mode SIW (HMSIW) technology [8]. The HMSIW technology preserves all advantages of the SIW technology and its size is reduced nearly by a half with lower design and fabrication complexity.

In [9], a left-handed and right-handed circular polarization (LHCP and RHCP) versions of a cavity–backed antenna based on HMSIW were proposed. Satisfactory performance was reached. The impedance bandwidth of both antenna versions was about 6% for the reflection coefficient (S_{11}) less than –10 dB, the axial ratio (AR) of 0.66% and 1.74% for AR less than 3 dB was reached for the LHCP and RHCP version of the antenna, respectively. The gain of both antenna versions was about 4.5 dBi. In [10], a semi-circular HMSIW cavity hybrid antenna was proposed. The antenna had a wide impedance bandwidth of 10% (for $S_{11} < -10$ dB) and the gain of 6.8 dBi. Unfortunately, the axial ratio of the antenna was only 1% (for $AR < 3$ dB). A common feature of both mentioned antenna concepts [9] and [10] is the fact that the antennas have single-layer configuration which is attractive due to a low cost fabrication process. In [11], an aperture-coupled dielectric resonator antenna fed by a HMSIW was proposed. Although such a dual-layer concept can bring better antenna performance, fabrication process of the antenna is difficult and the antenna cannot be called as a low profile antenna. In [12], a HMSIW circularly polarized antenna based on leaky-wave principles was presented.

In this paper, a half-mode substrate integrated waveguide U-slot antenna radiating left-handed circularly polarized wave is proposed. Its concept is simple and based on a linearly polarized HMSIW U-slot antenna [13]. The antenna has a single-layer configuration, good radiation performance, and can be easily fabricated by a printed circuit board process.

2. Proposed Antenna Configuration

The proposed antenna is depicted in Fig. 1. The dielectric substrate of the length L, the width W, and the height h with the relative permittivity ε_r, and the loss tangent $\tan(\delta)$ is on its both sides covered by metal sheets. The HMSIW is created by a row of vias and both its ends

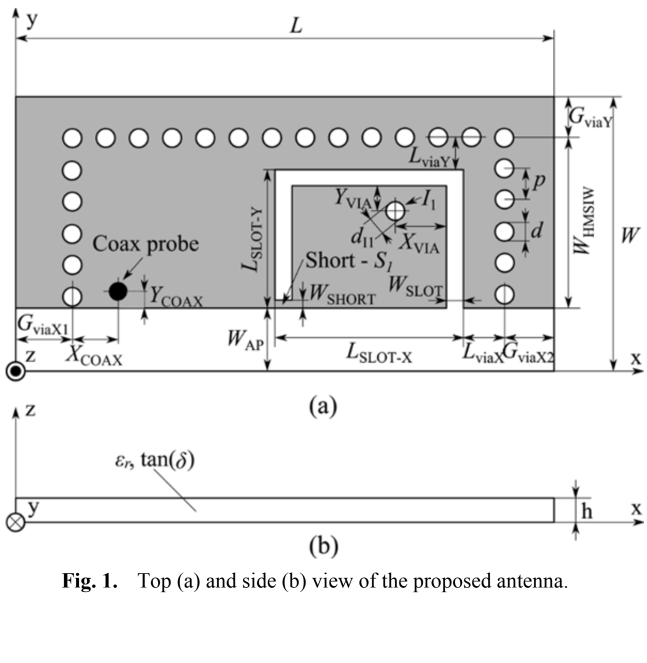

Fig. 1. Top (a) and side (b) view of the proposed antenna.

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are shorted. It operates in the fundamental mode $TE_{0.5,0}$ [8]. The radiating U-slot is etched in the top wall of the HMSIW at the distance L_{viaX} from its short end in the x-direction, and from the row of vias at the distance W_{viaY} in the y-direction. The outer dimensions of the slot are L_{SLOT-X} and L_{SLOT-Y}. The width of the slot is W_{SLOT}. The slot is shorted by the strip of the length L_{SHORT}. The shorting via is placed between the area bounded by the slot and the HMSIW bottom wall at the distances X_{VIA} and Y_{VIA} from the slot edges in the x- and y-direction, respectively. The antenna is equipped by a HMSIW-to-SMA transition.

The antenna radiates a left-handed circularly polarized wave in the boresight direction. The right-handed circularly polarized wave can be obtained by mirroring the antenna with respect to the x-z plane.

3. Antenna Design and Experimental Verification of the Antenna

The antenna design procedure can be divided into the following steps:

1. Design of the HMSIW using (8) – (13) presented in [8]. The waveguide should operate in the fundamental mode $TE_{0.5,0}$. The operating frequency of the antenna should be approximately 1.5 times higher than the cut-off frequency of the fundamental mode.

2. Preliminary determination of the slot dimensions. The lengths L_{SLOT-X} and L_{SLOT-Y} of the slot should be lesser than λ_m and a half of λ_m in the x- and in y-direction, respectively. (λ_m is the wavelength in the dielectric substrate at the design frequency). The best initial lengths L_{SLOT-X} and L_{SLOT-Y} of the slot should be approximately 0.75 λ_m and 0.4 λ_m in the x- and in y-direction, respectively. The width of the slot W_{SLOT} should be only several hundredths of λ_m, e.g. $\lambda_m/20$. The shorting via I_1 should be placed in the right half of the area bounded by the slot. The best placing of shorting via I_1 for further optimization is in the distance $X_{via} \sim 0.15\ \lambda_m$ and $Y_{via} \sim \lambda_m/5$ from the edge of the slot. The slot should be placed in the distance $\lambda_m/4$ from the coaxial probe.

3. Determination of the coax probe position. The coax probe should be placed in the distance approximately $\lambda_m/4$ from the shorted end of the HMSIW in the x-direction and as much as close the magnetic wall of HMSIW in the y-direction.

4. Application of the optimization process. In order to tune the antenna for desired operating frequency band, the optimization procedure with the combination of a full wave solver has to be applied.

The proposed antenna is designed with the help of time domain solver of CST Microwave Studio (CST MWS), where local optimizations Trust Region Framework and Nedler Mead Simplex Algorithm were used for the operating frequency of 10 GHz on the dielectric substrate ARLON Cuclad 217 with the relative permittivity $\varepsilon_r = 2.17 \pm 0.02$, tangent loss $\tan(\delta) = 0.0009$, and height $h =$ 1.524 mm. The resultant dimensions of the antenna are summarized in Tab. 1.

	[mm]		[mm]
L	37.5	Y_{COAX}	0.8
L_{SLOT-X}	14.6	X_{VIA}	3.25
L_{SLOT-Y}	7.2	Y_{VIA}	2.65
L_{viaX}	2.8	G_{viaX1}	4.2
W	18.0	G_{viaX2}	7.5
W_{HMSIW}	8.9	G_{viaY}	6.1
W_{SHORT}	0.3	H	1.524
L_{viaY}	1.7	d_{I1}	1.4
W_{SLOT}	1.1	D	1.4
W_{AP}	3.0	P	2.58
X_{COAX}	3.0		

Tab. 1. Dimensions of the proposed antenna (Fig. 1).

The distribution of the electric field in the substrate at the frequency 10 GHz is depicted in Fig. 2. Thanks to the shorting via I_1, the electric field at the slot rotates and the left handed circularly polarized wave in the far field is obtained. Simulated 3D radiation patterns for LHCP and RHCP at operating frequency 10 GHz are depicted in Fig. 3. The simulated realized gain is 5.99 dBi for LHCP.

To verify the proposed antenna concept (Fig. 1) experimentally, the antenna was fabricated (Fig. 4) by a low-cost etching PCB process with estimated precision of about tens of micrometers and drilled with Bungard CCD/ATC (Computer Controlled Drilling machine with Automatic Tool Change) with position accuracy of 20 ppm. The diameter of the tool which was used for drilling is 1.4 mm. The reflection coefficient was measured in a laboratory environment, the radiation patterns for the Theta range from –90° to 90° and the axial ratio were measured in an anechoic chamber. For the measurement, Rohde&Schwarz vector network analyzer ZVA67 was used. The results of the measurement are depicted and compared with the results from CST Microwave Studio in Figs. 5–7.

The simulated and measured reflection coefficient of the antenna is depicted in Fig. 5. The measured results are about 110 MHz shifted to higher frequencies in comparison to the simulated ones due to the manufacturing tolerance. The measured impedance bandwidth of the fabricated sample of the antenna is 11.9% (for $S_{11} < -10$ dB).

The simulated and measured axial ratio at the boresight direction (z-axis direction) versus frequency is plotted in Fig. 6. The measured results are shifted about 80 MHz to higher frequencies in comparison to the simulated ones. The measured axial ratio bandwidth is 2.2% (for $AR < 3$ dB).

The normalized simulated and measured radiation patterns in two orthogonal cutting planes at the frequency 10 GHz are depicted in Fig. 7. In the xz-plane, it can be observed that the radiation pattern is shifted about 8° in comparison to the simulated results. In the yz-plane, the simulated and measured values are in good agreement. The measured peak gain of the antenna is 6.0 dBi.

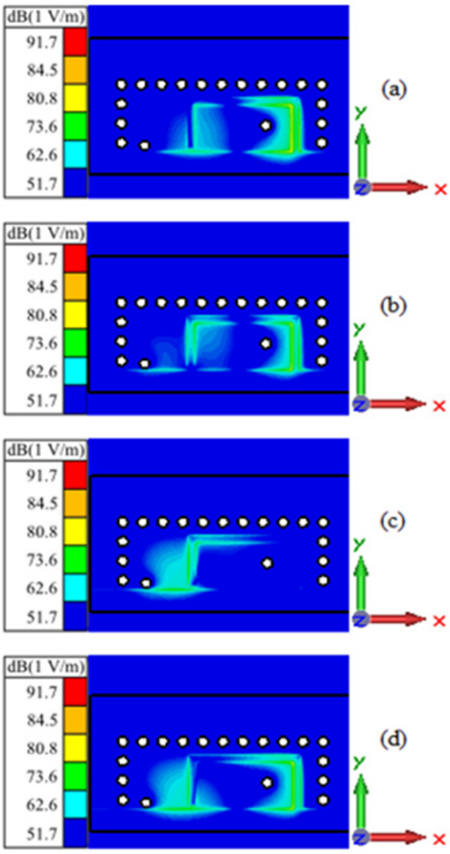

Fig. 2. Distribution of electric field intensity at 10 GHz in substrate (magnitude): (a) phase = 0°, (b) phase = 45°, (c) phase = 90° and (d) phase = 135°.

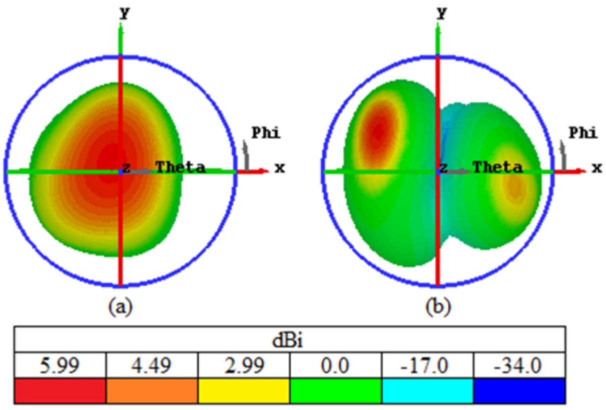

Fig. 3. Simulated radiation patterns of the proposed antenna (realized gain, f = 10 GHz): (a) LHCP and (b) RHCP.

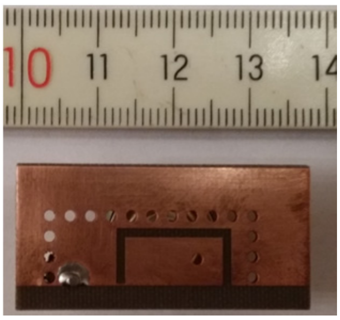

Fig. 4. Fabricated sample of the proposed HMSIW U-slot antenna.

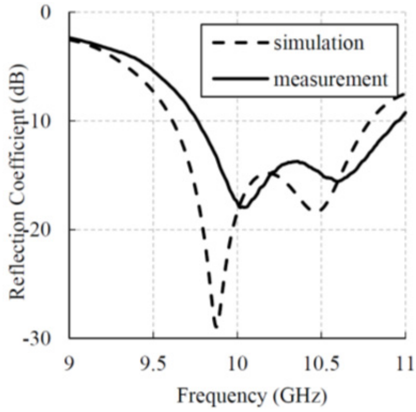

Fig. 5. Reflection coefficient of the proposed antenna.

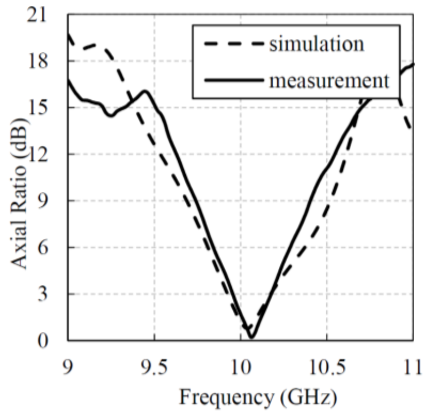

Fig. 6. Axial ratio of the proposed antenna.

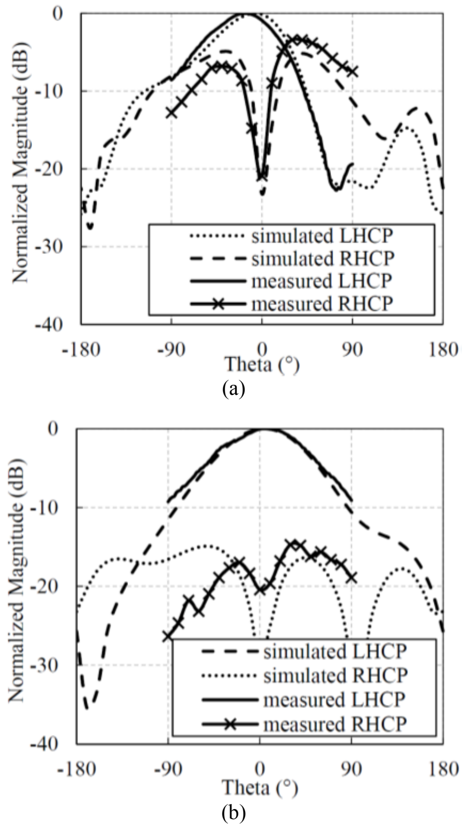

Fig. 7. Normalized radiation patterns of the proposed antenna: (a) xz-plane, (b) yz-plane.

Comparison of circularly polarized single layer HMSIW antennas is summarized in Tab. 2. Obviously, the proposed HMSIW antenna has a lower gain than SIW antenna presented in [6] ($BW = 10.3\%$, $G = 8.0$ dBi and $AR = 2.6\%$), but the size is reduced about 50%. Other parameters are almost the same. The proposed antenna has a wider impedance and axial ratio bandwidth than the antennas presented in [9] and [10]. The proposed antenna is smaller in comparison to other HMSIW antennas.

	impedance BW [%]	gain [dBi]	axial ratio BW [%]	size of antenna
Antenna with dielectric aperture [9]	6.0	4.2	0.7	$0.73\ \lambda_0 \times 0.22\ \lambda_0$
Hybrid antenna [10]	10.0	6.8	1.0	$1.45\ \lambda_0 \times 1.45\ \lambda_0$
Proposed antenna	11.9	6.0	2.2	$0.64\ \lambda_0 \times 0.24\ \lambda_0$

Tab. 2. Comparison of circularly polarized single layer HMSIW antennas (where λ_0 is wavelength in vacuum).

4. Parametric Study

To better understand antenna behavior, the parametric study of the antenna is carried out with help of CST MWS

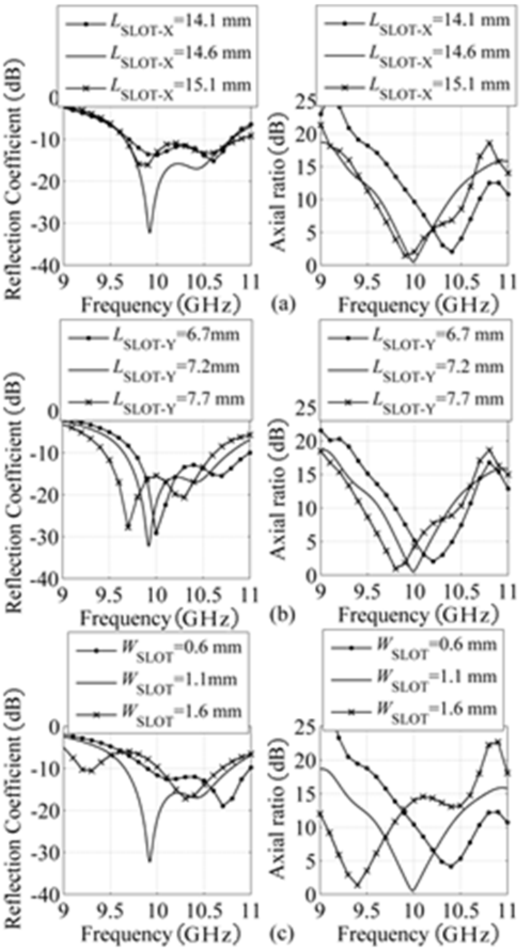

Fig. 8. The effect of the selected parameters on the reflection coefficient and the axial ratio of the proposed antenna: (a) length of slot L_{SLOT-X} in x-direction, (b) length of slot L_{SLOT-Y} in y-direction and (c) width of slot W_{SLOT}.

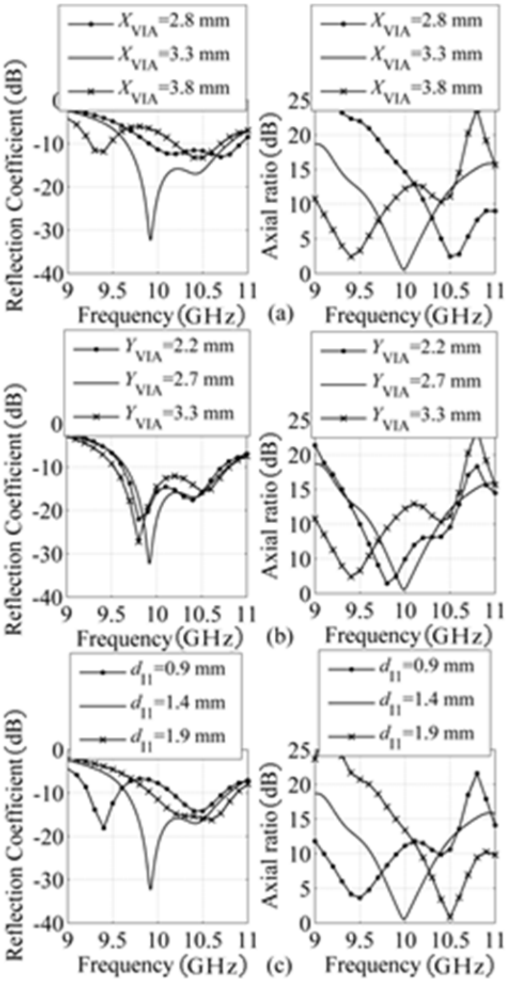

Fig. 9. The effect of the selected parameters on the reflection coefficient and the axial ratio of the proposed antenna: (a) distance X_{VIA} between the slot and the shorting via in x-direction, (b) distance Y_{VIA} between the slot and the shorting via I_1 in y-direction and (c) diameter of the shorting via I_1.

to demonstrate the effect of antenna geometrical parameters on the reflection coefficient and axial ratio. During this study all parameters given in Tab. 1 are kept and only one parameter is changed. The results are depicted in Fig. 8.

Figures 8(a) and 8(b) show the effect of varying the length of the slot in the x and y direction on the reflection coefficient and the axial ratio of the antenna. Decreasing the slot length L_{SLOT-X} (the x-direction) leads to the deterioration of the impedance matching and shift of the minimum of the axial ratio towards higher frequencies. Decreasing the slot length L_{SLOT-Y} leads to the shift of the operating frequency and the minimum of the axial ratio towards higher frequencies. Figure 8(c) shows the effect of varying the width of the slot W_{SLOT}. The change of the width of the slot has very strong effect on the impedance matching and the axial ratio of the antenna.

Figures 9(a) and 9(b) show the effect of varying the position of the shorting via in the x-direction and y-direction. Obviously, the change of the shorting via position in the x-direction (variation of the parameter X_{VIA}) has much stronger influence on the operating frequency and axial

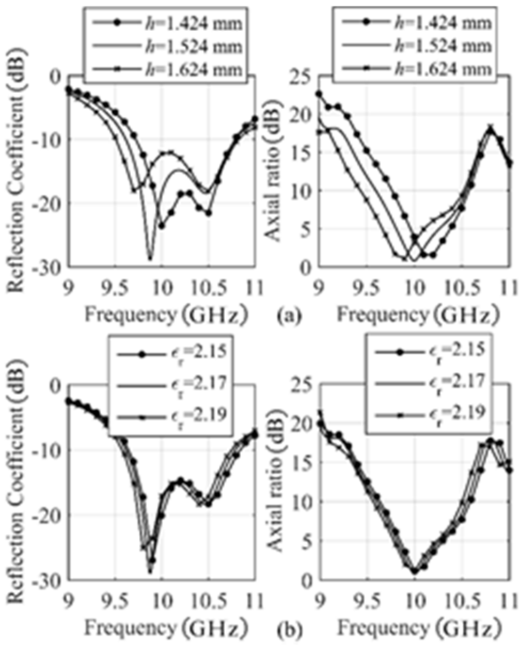

Fig. 10. The effect of the selected parameters of the substrate on the reflection coefficient and the axial ratio of the proposed antenna: (a) height *h* of the substrate and (b) dielectric constant ε_r of the substrate.

ratio than the variation of the in the y-direction (variation of the parameter Y_{VIA}).

Figure 9(c) shows the effect of varying the diameter of the shorting via I_1. The diameter of the shorting via I_1 influences the operating frequency and the minimum of the axial ratio. Decreasing the diameter of I_1 leads to the shift of the operating frequency and the minimum of the axial ratio to lower frequency and vice versa.

Figure 10(a) and 10(b) show the effect of varying parameters of the substrate. The height *h* of the substrate influences the operating frequency and the shift of the minimum of the axial ratio. Decreasing the height of the substrate h leads to the shift of the operating frequency and the minimum of the axial ratio towards higher frequencies and vice versa. Very small change of the dielectric constant ε_r has a very small effect on the operating frequency and axial ratio.

5. Conclusion

In this paper, a circularly polarized half-mode substrate integrated waveguide U-slot antenna operating in the X-band has been proposed. The manufactured sample of the proposed antenna achieves the impedance bandwidth of 11.9% (for $S_{11} < -10$ dB), the axial ratio bandwidth of 2.2% (for $AR < 3$ dB) and the realized gain of 6.0 dBi. The proposed antenna achieves better performance and it is smaller in comparison to other HMSIW circularly polarized antennas. The proposed antenna structure can be exploited e.g. as a basic element of an antenna array for satellite communication, or for energy harvesting applications or body-centric wireless communications (after the antenna redesign for a desired frequency band).

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References

[1] LUO, G. Q., SUN, L. L., DONG, L. X. Single probe fed cavity backed circularly polarized antenna. *Microwave and Optical Technology Letters*, 2008, vol. 50, no. 11 , p. 2996–2998. DOI: 10.1002/mop.23848

[2] LUO, G. Q., HU, Z. F., LIANG Y., et al. Development of low profile cavity backed crossed slot antennas for planar integration. *IEEE Transactions on Antennas and Propagation*, 2009, vol. 57, no. 10, p. 2972–2979. DOI: 10.1109/TAP.2009.2028602

[3] LUO, G. Q., SUN, L. L. A reconfigurable cavity backed antenna for circular polarization diversity. *Microwave and Optical Technology Letters*, 2009, vol. 51, no. 6, p. 1491–1493. DOI: 10.1002/mop.24393

[4] KIM, D., LEE, J. W., CHO, C. S., et al. X-band circular ring-slot antenna embedded in single-layered SIW for circular polarization. *Electronics Letters*, 2009, vol. 45, no. 13, p. 668–669. DOI: 10.1049/el.2009.0901

[5] KIM, D., LEE, J. W., CHO, C. S., et al. Design of SIW cavity-backed circular-polarized antennas using two different feeding transitions. *IEEE Transactions on Antennas and Propagation*, 2011, vol. 59, no. 4, p. 1398–1403. DOI: 10.1109/TAP.2011.2109675

[6] LACIK, J. Circularly polarized SIW square ring-slot antenna for X-band applications. *Microwave and Optical Technology Letters*, 2012, vol. 54, no. 11, p. 2590–2594. DOI: 10.1002/mop.27113

[7] XU, F., WU, K. Guided-wave and leakage characteristics of substrate integrated waveguide. *IEEE Transactions on Microwave Theory and Techniques*, 2005, vol. 53, no. 1, p. 66–73. DOI: 10.1109/TMTT.2004.839303

[8] LAI, Q., FUMEAUX, C., HONG, W., et al. Characterization of the propagation properties of the half-mode substrate integrated waveguide. *IEEE Transactions on Microwave Theory and Techniques*, 2009, vol. 57, no. 8, p. 1996–2004. DOI: 10.1109/TMTT.2009.2025429

[9] RAZAVI, S. A., NESHATI, M. H. Development of a low–profile circularly polarized cavity–backed antenna using HMSIW technique. *IEEE Transactions on Antennas and Propagation*, 2013, vol. 61, no. 3, p. 1041–1047. DOI: 10.1109/TAP.2012.2227104

[10] DASHTI, H., NESHATI, M. H. Development of low-profile patch and semi-circular SIW cavity hybrid antennas. *IEEE Transactions on Antennas and Propagation*, 2014, vol. 62, no. 9, p. 4481–4488. DOI: 10.1109/TAP.2014.2334708

[11] LAI, Q., FUMEAUX, C., HONG, W., et al. 60 GHz aperture-coupled dielectric resonator antennas fed by a half-mode substrate integrated waveguide. *IEEE Transactions on Antennas and Propagation*, 2010, vol. 58, no. 6, p. 1856–1864. DOI: 10.1109/TAP.2010.2046852

[12] SAGHATI, A. P., MIRSALEHI, M. M, NESHATI, M. H. A HMSIW circularly polarized leaky-wave antenna with backward, broadside, and forward radiation. *IEEE Antennas and Wireless Propagation Letters*, vol. 13, no. 4, p. 451–454. DOI: 10.1109/LAWP.2014.2309557

[13] HUBKA, P., LACIK, J. Linearly polarized HMSIW U-slot antenna. In *Proceedings of the Conference on Microwave*

Techniques (COMITE). Pardubice (Czech Republic), 2015, DOI: 10.1109/COMITE.2015.7120225

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