X-Band Circularly Polarized HMSIW U-Slot Antenna

Patrik HUBKA, Jaroslav LACIK

Dept. of Radio Electronics, Brno University of Technology, Technicka 12, 616 00 Brno, Czech Republic

xhubka00@stud.feec.vutbr.cz, lacik@feec.vutbr.cz

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.

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 (S11) 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 S11 < –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 εr and the loss tangent tan(δ) is on its both sides covered by metal sheets. The HMSIW is created by a row of vias and both its ends...
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 $L_{\text{VIA}}$ from its short end in the x-direction, and from the row of vias at the distance $W_{\text{VIA}}$ in the y-direction. The outer dimensions of the slot are $L_{\text{SLOT-X}}$ and $L_{\text{SLOT-Y}}$. The width of the slot is $W_{\text{SLOT}}$. The slot is shorted by the strip of the length $L_{\text{SHORT}}$. The shorting via is placed between the area bounded by the slot and the HMSIW bottom wall at the distances $X_{\text{VIA}}$ and $Y_{\text{VIA}}$ 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 $L_{\text{SLOT-X}}$ and $L_{\text{SLOT-Y}}$ of the slot should be lesser than $\lambda_m$ and a half of $\lambda_m$ in the x- and in y-direction, respectively. ($\lambda_m$ is the wavelength in the dielectric substrate at the design frequency). The best initial lengths $L_{\text{SLOT-X}}$ and $L_{\text{SLOT-Y}}$ of the slot should be approximately 0.75 $\lambda_m$ and 0.4 $\lambda_m$ in the x- and in y-direction, respectively. The width of the slot $W_{\text{SLOT}}$ should be only several hundredths of $\lambda_m$, 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 $X_{\text{VIA}} \sim 0.15 \lambda_m$ and $Y_{\text{VIA}} \sim \lambda_m/5$ 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.

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 $-90^\circ$ to $90^\circ$ 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 $8^\circ$ 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] \( (BW = 10.3\%, \ G = 8.0 \text{ dBi} \) 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.

<table>
<thead>
<tr>
<th></th>
<th>impedance BW [%]</th>
<th>gain [dBi]</th>
<th>axial ratio BW [%]</th>
<th>size of antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna with dielectric aperture [9]</td>
<td>6.0</td>
<td>4.2</td>
<td>0.7</td>
<td>( 0.73 \lambda_0 \times 0.22 \lambda_0 )</td>
</tr>
<tr>
<td>Hybrid antenna [10]</td>
<td>10.0</td>
<td>6.8</td>
<td>1.0</td>
<td>( 1.45 \lambda_0 \times 1.45 \lambda_0 )</td>
</tr>
<tr>
<td>Proposed antenna</td>
<td>11.9</td>
<td>6.0</td>
<td>2.2</td>
<td>( 0.64 \lambda_0 \times 0.24 \lambda_0 )</td>
</tr>
</tbody>
</table>

Tab. 2. Comparison of circularly polarized single layer HMSIW antennas (where \( \lambda_0 \) 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 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 \( L_{\text{SLOT-X}} \) (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 \( L_{\text{SLOT-Y}} \) 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 \( W_{\text{SLOT}} \). 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 \( X_{\text{VIA}} \)) has much stronger influence on the operating frequency and axial
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 $S_{11} < -10 \, \text{dB}$), the axial ratio bandwidth of 2.2% (for $AR < 3 \, \text{dB}$) 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).

Acknowledgment

The research described in this paper was financed by the Czech Ministry of Education in frame of the National Sustainability Program under grant LO1401. For research infrastructure of the SIX Center was used.

References

About the Authors …

Patrik HUBKA was born in Čeladná, Czech Republic, in 1987. He received his M.Sc. degree in Electrical Engineering from Brno University of Technology (BUT), Czech Republic, in 2012, and is currently working toward the Ph.D. degree in Electrical Engineering at the Dept. of Radio Electronics, Faculty of Electrical Engineering and Communication, BUT. His research interests include microwave circuits based on HMSIW.

Jaroslav LÁČÍK received the M.Sc. and Ph.D. degrees from BUT, Czech Republic, in 2002 and 2007, respectively. He is currently an Associate Professor at the Dept. of Radio Electronics, Faculty of Electrical Engineering and Communication, BUT. His research interests are antennas, body-centric wireless communication, and computational electromagnetics. He is a member of IEEE.