A high gain microstrip antenna based on substrate integrated waveguide technology for modern wireless communication

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Abstract. An antenna based on a Substrate Integrated Waveguide (SIW) is proposed in this paper as suitable for modern wireless applications. The presented antenna is formed of two elements; an active and a passive. The active element is directly connected to the feeding line while the passive element, which consists of three segments, is energised by coupling with the active element by a means of a gap. Dimensions of each segment is 3.63 × 19.5 mm². It was found that the antenna resonates at 16.98 GHz and has an impedance bandwidth of 985 MHz with a reflection coefficient of -35 dB. An overall gain of 9.44 dBi was further achieved with a total area of 30 × 23.5 mm². A substrate of Rogers Duroid 5880 with relative permittivity of 2.2 and thickness of 0.787 mm is adopted for the design of this antenna. Designing and simulating the antenna accomplished using the Microwave Studio Suite of Computer Simulation Technology (CST) simulator.

Keywords — high gain antenna, Yagi array antenna, substrate-integrated waveguide (SIW).

1. Introduction
Day to day, the need for high capacity is increasing as a result of the continuous evolution of wireless network applications. High bandwidths are required for this purpose, and conventional wireless systems still using frequencies up to 10 GHz, it is difficult to achieve high data rates due to limited bandwidth [1]. This requires a new design of antennas with significant characteristics that make them suitable for operation at frequencies higher than 10 GHz. The most prominent of these characteristics is high gain, though other characteristics such easy fabrication, low profile, and low insertion losses [2].

Generally, conventional microwave system elements have several advantages like a high gain antenna that are not available in planar (microstrip) elements so that to mirror these advantages in planar elements, this requiring seeking for methods for this purpose. The most appropriate methods used for the above purpose is the one based on the technique of substrate integrated waveguide (SIW) [3]. As a result, the SIW technique conveys the advantages of both planar (microstrip) components and the conventional microwave components. An SIW can be symbolized as fabrication of planar structure such that top metal layer and bottom ground layer are connected via a metallic cylinder called via holes in the form of two periodic rows [4].
This combination of advantages has prompted previous researchers to use this technique for the design of high gain antennas [5]-[12], filters [13]-[16], and power divider [17] for modern wireless communication systems. Many such high gain microstrip antennas, such as Yagi or Yagi-Uda antenna have been designed based on the SIW technique. The approach taken to such design depends on more than mode like full mode SIW (which is abbreviated SIW), half mode SIW and quarter mode SIW.

A microstrip Yagi antenna based on half-mode substrate integrated waveguide (HMSIW) technology is presented in [5]. The purpose of using HMSIW is to offer the driven element. The obtained gain is about 7.9 dBi at a frequency of 10 GHz. A magnetic Yagi antenna in X band was introduced in [6] such that a coupling patch is inserted between the driven element and the first director to improve impedance matching; the peak gain there was between 7.26dBi and 8.98dBi in the resultant band. In [7], a SIW- Yagi antenna was proposed such that the director element was divided into two parts on both surfaces, that is, the upper and lower surfaces of the substrate, to increase the gain of the proposed antenna to 9.46 dBi at 10.0 GHz. In [8], the HMSIW Yagi antenna was combined with a mirrored arrangement of a Yagi array to eliminate cross polarization and to enhance linear polarization. The obtained peak gain was between 6.0 and 7.9 dBi in the 10.5% relative bandwidth at a frequency of 10 GHz. The proposed Yagi antenna in [9] was fed by a slow-wave half-mode substrate-integrated waveguide to obtain a peak gain of 7.49 dBi within a bandwidth of 4 GHz, while a SIW quasi-Yagi antenna was presented in [10] by using the SIW-to-coplanar stripline (CPS) transition in order to reduce mutual coupling. The maximum gain within the entire bandwidth of the latter was 7.5 dBi at 9.5 GHz. A SIW Yagi-Uda antenna for 60 GHz applications was also presented in [11], showing achievable gains of 12 dBi; however, this required an increase in the number of directors to 18, indicating an unavoidable increase in antenna size.

2. Antenna Design

The antenna proposed in this paper mainly consists of two elements: active and parasitic. The active element is directly connected to the feed line while the other element is excited by coupling with the active element through a gap, g, which is fixed between them and accessed by via holes, as shown in figure 1, with dimensions as indicated in Table 1. The proposed antenna was fixed on the top layer of a substrate of Rogers Duroid 5880 with \( \varepsilon_r \) of 2.2, tangent loss of 0.001, and thickness of 0.787 mm. Simulating and performance evaluation of the presented antenna was done in CST Simulator [20].
The active element in this antenna takes the form of a semi-circle with an arrangement of via holes which represent the SIW segment. The main idea of the design for this antenna is essentially similar to that of Yagi-Uda antenna [18], and the active element in the proposed antenna thus represents the driven element, and the parasitic element represents the director element. The purpose of adopting the ideas behind the Yagi-Uda antenna due to the brilliant is its excellent set of characteristics, including high directivity and gain. The use of the semi-circle arrangement of SIW via holes concentrates the radiated power in one direction to ensure minimization of backward direction and maximization of the front to back ratio (F/B).

The diameter of the via holes \( d \) and the spacing between them is mandated by equation 1 [19].

\[
d \leq \frac{\lambda_g}{s} \quad \text{and} \quad p \leq 2d
\]

where

\( d \): the diameter of each via

\( p \): the space between two via

\( \lambda_g \): the guided wavelength

\[
\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}
\]

Further study has been done by dividing the parasitic element into a number of segments (three segments), such that each one has dimensions of 19.5 × 3.63 mm, and spacing these at a distance of 0.65 mm, as shown in figure 2; all dimensions of the proposed antenna are listed in Table 2.
Figure 2: Structure of the proposed antenna with dividing parasitic element

Table 2. Dimensions of the proposed antenna.

| parameter | $L_f$ | $L_m$ | $d_m$ | $R_c$ | $g$ | $W_p$ | $L_p$ | $L_h$ | $y$ |
|-----------|-------|-------|-------|-------|-----|-------|-------|-------|-----|
| value(mm) | 6.4   | 5     | 2     | 9.6   | 0.65| 19.5  | 3.63  | 10.55 | 0.6 |

The obtained structure and results of this operation mentioned above are illustrated in figures 3, and 4, respectively.
Figure 3: Antenna structure with three cases (a) one segment (b) two segments (c) three segments.

Figure 4: Simulation result $S_{11}$-parameter of the proposed antenna in three cases.

All results are summarized in Table 3:

| Ant. Topology | 3-segment | 2-segment | 1-segment |
|---------------|-----------|-----------|-----------|
| Freq.         | 16.98     | 16.98     | 16.98     |
| Gain          | 9.5 dBi   | 10.19 dBi | 9.487 dBi |
| S11           | -35 dB    | -23 dB    | -30.7 dB  |
| BW            | 1.02 GHz  | 930.9 MHz | 974.2 MHz |

It is clear that case of two segments is better than that of three segments in terms of resultant gain, yet adding of the third segment played a role only in improving the matching level ($|S_{11}| = -35$ dB).
3. Effect of Antenna Parameters

i. **Varying y-parameter (width of inset feed):**
   As seen in figure 5, which represents variation of the y-parameter, increased values of y increase the matching level, and the bandwidth also tends to increase. This increase is limited, however, and when the value of y extends by 0.6 mm, the matching level tends to decrease.

![Figure 5: Simulation of S_{11} for varying y-parameter.](image)

ii. **Varying L_f (length of inset feed):**
   Figure 6, which represent the variation of L_f–parameters (length of inset feed), shows that when the value of this parameter is increased, the matching level also increases, along with the bandwidth, until the value reaches 6.4. After this value, the matching level tends to decrease.

![Figure 6: simulation response for varying L_f parameter.](image)

iii. **Varying g (gap between each segment):**
   The gap between segments has an effective impact on the coupling between those segments and the coupling with the driven element. Changing this gap led to obtaining maximum matching when the gap value tended to 0.65 mm, as illustrated in figure 7.
Figure 7: Simulation of $S_{11}$-parameters on varying $g$-parameter.

The performance of the proposed antenna in this paper is illustrated in figure 8, which shows a frequency centred at 16.98 GHz with a reflection coefficient of -35 dB and a bandwidth of about 985 MHz. The 3-D far-field radiation pattern at 16.98 GHz with a gain of 9.5 dBi and directivity of 9.68 dB is illustrated in figure 9.

Figure 8: Simulation response of $S_{11}$ of the proposed antenna.
Figure 9: Far-field 3-D-plot directivity of the proposed antenna.

4. Electric Field (E-field), Magnetic Field (H-field) patterns and Current Distribution

The radiation pattern in the polar plot of E-field and H-field at resonant frequency 16.98 GHz is shown in figure 10 in three planes. Figure 10 (a) shows the X-Y plane ($\theta =90^\circ$), where the main lobe direction is 0 degree for the E and H-plane, and the magnitude of the main lobe is 18 dBV/m and -33.5 dBA/m. Figure 10 (b) shows the Y-Z plane ($\Phi =90^\circ$), where the main direction is 0 degree for the E and H-plane, and the main lobe magnitude is 20.7 dBV/m and -30.8 dBA/m. Figure 10 (c) shows the X-Z plane ($\Phi =0^\circ$), where the direction of the main lobe is 26 degrees for the E and H-plane, and the main lobe magnitude is 24.2 dBV/m and -27.3 dBA/m respectively. It is worthy to mention that the main beam directivity of the antenna makes an angle with the antenna plane due to the effect of the arrangement of via holes which concentrate the field in limited area. Also the effect of the three passive elements (segments) plays a role in determine of direction.
It is evident that the distribution of the surface current at the resonant frequency clusters at the inset slot beside the upper edge of the active element, as shown in figure 11; a large amount of current also concentrates in the first segment due to the high coupling with the active element, whilst a smaller amount of current is also found at the lower edge of the second segment. Only low current exists in the third segment because of the weak coupling there with respect to the active element.

Figure 11: surface current distribution of the proposed antenna at 16.98 GHz.
5. Conclusion
In this paper, a SIW Yagi antenna is presented. The presented antenna has an active element with via holes arranged in the form of a semi-half circle, while the passive element consists of three segments. It is found that the gap between the adjacent segments played an active role in determining the matching level. Also the number of segments has a role in determine the value of both gain and bandwidth. A high gain is obtained with two segments while large bandwidth is achieved with three segments. The resultant peak gain is 9.5 dBi at a frequency of 16.98 GHz, and bandwidth tends to 1.09 GHz with a reflection coefficient of approximately -35 dB. The total area occupied by this antenna is 30 × 23.5 mm².

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