SIW-induced dualmode dualband loop antenna: A new design insight and guideline

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Abstract
A quasi-omnidirectional printed antenna has been developed using Substrate Integrated Waveguide (SIW) technology. The radiating element is realized from a concept of segmented circular SIW cavity through repetitive bifurcation by magnetic walls and also by reshaping its ground plane. The conjecture and design insight have been discussed and demonstrated indicating matching bandwidth of 7.7% (3.49–3.77 GHz for TM_{010}-like mode) and 21.3% (5.08–6.29 GHz for TM_{020}-like mode). As much as 2 dBi gain with nonuniform quasi-omnidirectional radiation patterns has been experimentally documented. This work should find applications in compact wireless transceivers operating in WiMAX (IEEE 802.16) and WLAN (IEEE 802.11) bands.

1 | INTRODUCTION

The rapid development in wireless communication systems has prompted the need of portable as well as multifunctional devices. Commonly known techniques involve the use of high permittivity substrates/superstrates, magneto-dielectric materials, and capacitive loading. Multiband design introduces slots, stubs, and metamaterials. But most of them are poor in efficiency and also their size reduction is limited to $\frac{\lambda}{24}$. A different approach using substrate integrated waveguide (SIW) technology was explored very recently in Ref. [9]. There, a small geometry bearing the 64th mode, i.e., 1/64th section of a circular parch was realized as a SIW-variant of a planar monopole. That demonstrated quasi-omnidirectional radiations occurring at its fundamental resonant mode.

The SIW monopole shows few limitations: (i) the ground plane width ($\frac{\lambda}{24}$) is 6 times larger than that of the primary radiator; (ii) its higher order resonances do not help in effective antenna radiations.

In this paper, we have tried to alleviate all these shortcomings by replacing the large ground plane by a sleek configuration of equal width of the 1/64th element which indeed transforms the planar monopole to a loop-like structure. This actually helps in improving the modal characteristics where two successive modes have been successfully employed in this design in realizing dualmode dualband operation with quasi-omnidirectional radiation patterns.
3.77 GHz) which turns the antenna to a full-wavelength loop and (ii) TM020-like mode (5.08–6.29 GHz). As much as 7.7% matching bandwidth for the first mode and 21.3% bandwidth for the second radiating mode have been experimentally demonstrated showing about 2 dBi gain. This study helps us also in proposing a comprehensive design guideline for any practicing engineer intending to develop small wireless transceiver systems.

2 | SIW-INDUCED LOOP AND CHARACTERISTICS

The proposed antenna configuration is shown in Figure 1. It is actually a 1/64th section of circular SIW \( (a = \frac{2\pi r}{64}) \) with a sleek ground plane having width \( g_2 \approx a \). The basic philosophy of realizing such a section by introducing magnetic walls was discussed in Ref. [9]. It would be relevant to note that we cannot increase the number of segments infinitely. The open side walls then become too close to each other causing interaction with the adjacent fringing fields and destroying the basic modal characteristics.

The structure now represents a loop-like quasi-planar structure with loop-perimeter \( \approx 2d_4 + 2g_1 \). The gap parameter \( g_1 \) is kept small \( (g_1 \leq g_2) \). Copper vias of diameter \( d_{\text{via}} \) indicated by six white dots on the black metal surface, are vertically inserted and soldered with an extended ground plane \( (d_e \approx 2 \times d_{\text{via}}) \) on the reverse side. The grounded strip maintains the curvature of the shorted electric wall. In this design, the antenna dimension is made as compact as possible and therefore the ground plane extension has been deliberately reduced to \( d_1 \approx d_2 \approx 0.05 \times r \).

In a 1/64th loop configuration, we have conjectured two TM\(^2 \) modes (TM010 and TM020) as shown in Figure 2. Thus, it can be segmented theoretically by \( n \) number of quasi-magnetic walls passing through the center. The resonant frequency of TM\(_{nm0} \) mode is given by:

\[
f_{\text{TM}_{nm0}}(\text{conventional}) = \frac{1}{\pi \sqrt{\mu \epsilon}} \left( \frac{p_{nm}}{d} \right)
\]

where \( d = 2r \), \( r \) being the radius of the cavity and \( p_{nm} \) is the \( n \)th zero of Bessel’s function of order \( n \).

Now, when we segregate the cavity into quarter (1/4th section) and higher modes, its radius is found to determine the operating frequency as,

\[
f_{\text{TM}_{nm0}}(\text{modified}) \approx \frac{1}{\pi \sqrt{\mu \epsilon}} \left( \frac{p_{nm}}{r} \right)
\]

The \( S_{11} \) characteristics of the SIW loop depicted in Figure 3A indicates distinct dual resonances occurring around 3.55 and 5.8 GHz where the first one corroborates the resonance obtained in Ref. [9]. The loop-length \( (\approx 2d_4 + 2g_1 \approx 80 \text{ mm}) \) is in close approximation with \( \lambda_1 (\approx 84 \text{ mm}, \text{1st resonance}) \) and \( 1.5 \times \lambda_2 (\approx 78 \text{ mm}, \text{2nd resonance}) \). Now an eigen-mode analysis is presented in Table 1 to verify the conjecture and identify the modes. For the analysis using \( a \), the structure was

**FIGURE 1** Configuration of the proposed SFMSIW-induced antenna: (A) top and bottom views (bottom view has been shown dotted) and (B) perspective view. [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 2** Magnitude of total field distribution of circular SIW cavity in (A) TM010 mode and (B) TM020 mode (-----: E field, -----: H field)

**FIGURE 3** 3D view of a (A) SIW (a) and (B) SFMSIW: side-views (a) and top views (b) of the SFMSIW with radiating patch and SMA connector. [Color figure can be viewed at wileyonlinelibrary.com]
enclosed in an air box with electric walls. A vertical space $5h$ and lateral space $0.6r$ were provided. Electric fields in column 1 (SIW cavity with full ground plane) closely corroborate TM$_{010}$ and TM$_{020}$ modes of Figure 2. The field portrays in column 2 (truncated small ground plane) ensure the same modal nature as in column 1 and thus help in working with these modes in SIW-induced loop type antenna.

But the SIW-loop is different from a traditional loop, ie, Figure 4A. A comparison of their $S_{11}$ (Figure 4B) shows that the 1st resonance mutually corroborate but the 2nd ones fail. The radiations of the 2nd resonance also significantly differ from each other: SIW-loop provides 1.9 dBi gain which for traditional loop keeps only 0.2 dBi.

### 3 | EXPERIMENTS AND VALIDATION

A prototype has been fabricated on Rogers RT/Duroid 5880 by our in-house facilities such as MITS 21T Precision Machine. The top and bottom views of the prototype are shown in Figure 3B,C, respectively. Rosenberger’s 32K101-400L5 SMA connector has been used to feed the antenna. It was measured using Agilent’s E5071C ENA Series Network Analyzer and a semi-automated Anechoic Chamber. Some representative results are presented in here.

The simulated and measured $S_{11}$ values are shown in Figure 5A. The measurements are found to closely agree with the simulated results. Measured $-10$ dB bandwidth of 7.7% (3.49–3.77 GHz) for TM$_{010}$-like mode and 21.3% (5.08–6.29 GHz) for TM$_{020}$-like mode exactly follow the simulated predictions.

Its principal plane radiation patterns obtained at 3.54 and 5.5 GHz are shown in Figures 6 and 7, respectively. As conjectured, both resonant modes produce nonisotropic omnidirectional radiations. The concept of loop makes considerable

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Eigen-mode performance newly conceived SIW loop compared with conventional SIW cavity</th>
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<tbody>
<tr>
<td>Full ground plane (gray shade) and electric field</td>
<td>Proposed fractional ground plane (gray shade) and electric field</td>
</tr>
<tr>
<td>3.52 (TM010)</td>
<td>3.5 (TM010-like)</td>
</tr>
<tr>
<td>5.60 (TM020)</td>
<td>5.58 (TM020-like)</td>
</tr>
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</table>
change in the radiation patterns compared to those of treated as SIW-monopole. The measurements are found to follow the simulated predictions, but a lack of close mutual correspondence is observed, especially in Figure 7A,B. The main reason is the lack of pattern symmetry in radiation fields and its rapidly changing nature with the angles as revealed from the 3D portrayals in Figure 8. Therefore, even a very little or nominal misalignment in the measurement setup would cause considerable deviation from the theoretical data and that is observed in our case. Their cross-polar levels are over 10 dB down compared to the copolar peak levels. Linear polarization of the proposed antenna is confirmed. The peak gain varies from 2.1 to 1.9 dBi. A study has been depicted in Figure 5B based on simulated and measured data at its two operating bands.
The radiation efficiency of the antenna has been measured using Wheeler cap technique and its theoretical calculation can be seen from Ref. [12]. The measured results have been obtained by averaging 15 samples ($S_{11}$ values under different boundary conditions) in each case and are 76.5% (Simu: 77.6%) and 79.3% (Simu: 79.51%) for the 1st and 2nd modes, respectively, which closely corroborate the simulated predictions.

4 | DESIGN GUIDELINES

This study helps us in formulating few necessary steps to design the proposed antenna for any practical applications. They are briefly stated as follows:

1. Low loss thin PTFE substrate with typical values of $\varepsilon_r$ 2.2–2.3 and thickness $= 1–2\, \text{mm}$ is recommended. Also, the $h/l$ ratio should be $< 2$ to operate with TM$_{010}$ mode, which is our mode of interest.

2. An estimation for $r$ can be determined for TM$_{010}$ mode to resonate at a given frequency say $f_{\text{TM}_{010}}$ (following Equation 2). With this $r$ value, an eigenmode analysis needs to be performed to have a primary knowledge of the modes in a true cavity.

3. The parameters relating to the metallic vias may be determined as: $d_{\text{via}}/\lambda_0 < 0.1$, $d_{\text{gap}} < 2 \times d_{\text{via}}$, where $d_{\text{gap}}$ is
the via-to-via center separation, and $\lambda_0$ is the resonant wavelength for the first resonance.

4. An increase in $r$ decreases $d_3/d_4$ ratio pushing the feed toward O. The field being maximum near O, experiences gradually increased perturbation as $r$ increases. This perturbation would affect the 2nd mode predominantly and cause an increase in modal separation as experienced in Ref. [15]. Such an increase in modal separation is also evident in Figure 9.

5. The ground plane dimensions:
   - $g_2 \approx a$, and $g_1 \approx 0.75 \times g_2$. The effect of $g_2$ on the impedance and gain values is examined in Figure 10A, B. Wider $g_2$ values help in improving both gain and impedance matching. $G_1$ controls fringing field or coupling effects and influences the input impedance and gain as examined in Figure 11. Moderate value of $g_2 = a = 4.7$ mm and $g_1 = 3.5$ mm are recommended to be an optimum choice.

**TABLE 2**  Comparison of performances of the proposed antenna with earlier designs

<table>
<thead>
<tr>
<th>Type of Antenna</th>
<th>Dimension $(\times 0.02)$</th>
<th>Matching BW (%)</th>
<th>Gain (dBi)</th>
<th>Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIW$^{16}$</td>
<td>0.414</td>
<td>4.8/21.6</td>
<td>4.12/~6</td>
<td>Broad/Broad</td>
</tr>
<tr>
<td>SIW$^{17}$</td>
<td>0.448</td>
<td>1.55</td>
<td>5.9</td>
<td>Broad</td>
</tr>
<tr>
<td>Metamat.$^{18}$</td>
<td>0.291</td>
<td>3</td>
<td>0.79</td>
<td>Omni</td>
</tr>
<tr>
<td>PIFA$^{19}$</td>
<td>0.291</td>
<td>24.5</td>
<td>5</td>
<td>Broad</td>
</tr>
<tr>
<td>This work</td>
<td>0.1216</td>
<td>7.7/21.3</td>
<td>2.1/2.3</td>
<td>Omni/Omni</td>
</tr>
</tbody>
</table>

Broad: Broadside, Omni: Omnidirectional.
• Extended ground-strip should follow the curvature of the section HC and \(d_r \approx 2 \times d_{\text{agt}}\).

6. The feed dimensions:
• Width \(w\) needs to be determined using any standard microstrip line calculator available online.

The feed location \(d_3\) from O is \(\approx 0.25 \times r\) which may need fine tuning to obtain 50Ω impedance matching.

5 | CONCLUSION

This work presents a new class of miniaturized “hybrid” SIW antenna, which can be used to obtain quasi-omnidirectional radiation patterns. A relative comparison of the present antenna with some earlier SIW, metamaterial based miniaturized antennas and PIFA are presented in Table 2. This is self-explanatory revealing its suitability and superiority in terms of the operating bandwidth, size, and gain.

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Dual-/triple-wideband microstrip bandpass filter using independent triple-mode stub-loaded resonator

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