A review on future planar transmission line

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Ashok Kumar¹, Garima Saini¹ and Shailendra Singh²*

Abstract: Substrate Integrated Waveguide (SIW) is an emerging trend in planar technology. The SIW structure consists of two rows of conducting cylinders in a dielectric substrate. The average power-handling capacity of an SIW structure is primarily determined by its substrate materials and its geometric topology. The power-handling capability depends on the nature of SIW circuits. Microwave and millimeter wave components can be integrated on SIW. It acts as a bridge between planar and non-planar technology. By using innovative fabrication techniques, SIW technology combines the classical planar circuits and metallic waveguide. The animus of the study is to provide the idea on design and fabrication of SIW structures and comparison between different topologies used for size reduction and dominant mode bandwidth enhancement.

Subject: Telecommunication

Keywords: SIW; millimeter waves; SIW cavity; Q-factor

1. Introduction
The Substrate Integrated Waveguide (SIW) technology represents an emerging approach for the implementation and integration of microwave, millimeter components. SIW permits to realize traditional rectangular waveguide components in planar form. It is compatible with planar processing techniques such as standard printed circuit board (PCB) or low-temperature co-fired ceramic (LTCC) technology (Bozzi, Georgiadis, & Wu, 2011). SIW structures are used for many applications in microwave, millimeter wave and broadband wireless communications. SIW are high-density integration technique structures implemented by using two rows of conducting cylinders or slots in a dielectric substrate that electrically connect two parallel metal plates.

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PUBLIC INTEREST STATEMENT
Cell phones, Television, Radio etc. all these components are important part of our daily life. In all these we are using antenna, filter, couplers etc. as an integrating components. Day by day we are trying to miniaturize the things by using small size integrated components but these components can operate at very low power and fabrication of all these components on a chip is very difficult. So to reduce this small size and low power handling problem we are using a different type of medium which can provide a facility to design small size components on a single chip which are capable to handle moderate power also.
SIW technology allows integration of passive components; active components and antennas in a single substrate, due to this it reduce losses and parasitic effects (Bozzi, Perregrini, & Wu, 2008). Basically, the waveguide are the best transmission line for high power and high-frequency application. Planar transmission line has the advantage of operation at low frequency but suffers from power handling capacity. SIW is basically a combination of waveguide and planar transmission lines. It has moderate power-handling capacity and it is planar also. It is also referred as the “laminated waveguide”. In laminated waveguide, the electromagnetic wave leakage is prevented by using conductor side wall via holes smaller than a quarter wavelengths (λ/4) (Hiroshi, Takeshi, & Funii, 1998).

Rectangular waveguides have been mostly used in the implementation of microwave and millimeter-wave components and systems with their features such as low insertion loss, high-quality factor (Q-factor) with high power-handling capability. The waveguide have some disadvantages such as bulky size, complex manufacturing and non-planar geometry (Tarck & Ke, 2013).

2. SIW characteristics

There are three types of losses present in the SIW structure i.e. conductor loss, dielectric loss and radiation loss (Bozzi et al., 2008). The conductor loss (α_c) is due to the finite conductivity of metal.

Conductor loss can be decreased by using highly conductive metal with increased substrate height. Dielectric loss (α_d) occurs due to finite conductivity of dielectric substrate. The radiation loss occurs in structure due to the energy leakage through the gaps. The conductor loss (α_c) and dielectric loss (α_d) is explained as (Deslandes & Wu, 2006)

\[
\alpha_c = \frac{R_s \left( 2h\pi^2 + k^2 \right)}{k^2 h \beta \eta} \tag{1}
\]

\[
\alpha_d = \frac{k^2 \tan \delta}{2 \beta} \tag{2}
\]

\[
\tan \delta = \frac{\sigma}{\omega \epsilon} \tag{3}
\]

where, \( \alpha_c \) is the conductor loss, \( \alpha_d \) is the dielectric loss; \( \beta \) is the phase constant, \( k \) is the free space wave number; \( h \) is the height of substrate, \( \tan \delta \) is the dielectric loss tangent; \( \eta \) is the intrinsic impedance of the medium; \( R_s \) is the surface resistivity of the conductors; \( \sigma \) is the conductivity; \( \epsilon \) is the permittivity.

Dielectric loss is not affected by the geometry of SIW structure, so it can be minimized by using good dielectric substrate. Radiation losses can be minimized by keeping space \( p \) small and diameter \( d \) of the vias large. The radiation losses can be overcome by using condition as \( p/d < 2.5 \) (Bozzi, Pasian, Perregrini, & Wu, 2009). SIW modes practically coincide with a subset of guided modes of the rectangular waveguide, such as TE_{mn} modes with \( n = 1, 2, ... \) and so on. TM modes are not supported by SIW due to the gaps between metal vias. In fact transverse magnetic fields determine longitudinal surface currents, which are subject to strong radiation due to presence of the gap (Daniels & Heath, 2007). If slots cut the surface current, a large amount of radiation will appear and if the slots are cut along the direction of flow of surface current then there is only small amount of radiation takes place as shown in Figure 2 (Xu & Wu, 2005).

\[
\vec{n} \times \vec{H} = \vec{J}_s \tag{4}
\]

where, \( \vec{n} \) = unit vector normal to the surface; \( \vec{H} \) = magnetic field intensity; \( \vec{J}_s \) = electric surface current density.
The design analysis is explained in terms of size and bandwidth. Cut-off frequency of the fundamental mode is determined by the width of the SIW. In recent years, there are different waveguide topologies have been proposed to improve the compactness and bandwidth of the SIW structures (Bozzi et al., 2011). The different topologies have been applied for the size reduction of SIW i.e. Substrate Integrated folded Waveguide (SIFW), Half-mode Substrate Integrated Waveguide (HMSIW), Folded Half-mode Substrate Integrated Waveguide (FHMSIW), and Quadri-Folded Substrate Integrated Waveguide (QFSIW). In the SIFW, a metal septum permits folding of the waveguide, thus reducing the waveguide width by a factor of \((9\varepsilon_r)^{-1/2}\) which is depicted in Figure 3 (Grigoropoulos, Sanz-Izquierdo, & Young, 2005)

In Figure 4, the HMSIW permits the compactness early 50% which is based on the approximation of vertical cut of the Waveguide as virtual magnetic wall (Lai, Fumeaux, Wei, & Vahldieck, 2009). The FHMSIW is the combination of SIFW and HMSIW which help in size reduction (Zhai, Hong, & Wu, 2008).

The Quadri-folded Substrate Integrated Waveguide is designed using a special C-type slot in the middle conductor layer which is shown in Figure 5 (Zhang, Cheng, & Fan, 2011).

The comparison in topologies for size reduction is shown in Table 1.
For the bandwidth improvement, the topologies used are Substrate Integrated Slab Waveguide (SISW) and Ridge SIW.

In SISW, the dielectric medium is periodically pricked with air-filled holes, which are located in the lateral portion of the waveguide (Bozzi et al., 2005). In this approach, bandwidth was enhanced shown as in (Figure 6).

Ridge was applied through a row of thin, partial-height metal posts located at the center of the longer side of the waveguide. This modification is shown in Figure 7 (Che, Li, Russer, & Chow, 2008).

The comparison in topologies for bandwidth enhancement is shown in Table 2.

Low-loss material is the foundation for developing high-performance-integrated circuits and systems. The material selection is very critical for antenna development. The most used materials for

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**Table 1. The comparison in topologies for size reduction**

| SIW Topology       | Size reduction approx. (%) |
|--------------------|----------------------------|
| HMSIW (Lai et al., 2009) | 50                         |
| FHMSIW (Zhai et al., 2008) | 75                         |
| QFSIW (Zhang et al., 2011) | 89                         |

**Table 2. The comparison in topologies for bandwidth enhancement**

| SIW Topology | Enhancement of bandwidth approx. (%) |
|--------------|--------------------------------------|
| SISW (Bozzi et al., 2005) | 40                                   |
| RSIW (Che et al., 2008) | 73                                   |
above-mentioned topologies are Rogers RT/duroid® 5880 glass microfiber-reinforced PTFE composite and RT/duroid® 6002 for conventional PCB processing, which are easily sheared with laser and machined to the required shape. The holes can be easily drilled mechanically into these materials compared to ceramics (Tarck & Ke, 2013). The dimensional stability and a good thermal stability of the material is the important consideration in the SIW design. The novel materials as plastic, paper and textile are helpful to design cost-effective components in the field of academic and industrial research for various microwave applications. SIW antennas were fabricated using polyethylene terephthalate (PET) substrate (Moro, Collado, Via, Georgiadiis, & Bozzi, 2012). It is a flexible and cheap substrate material for the development of microwave components. Paper is another easily available, eco-friendly and cheap material for SIW fabrication. The electronic circuit can be implemented on paper by ink-jet printing and there is no need of chemical etching or use of acids. The SIW interconnects and components on paper substrate by ink-jet printing were implemented (Moro, Kim, Bozzi, & Tentzeris, 2012). The paper-based implementation is well suited for the design of SIW components and used for conformal shape, arbitrary geometry and multilayered configuration. The textile material is used for the fabrication of a wearable SIW antenna (Agnieszens, Bozzi, Moro, & Rogier, 2012).

The average power-handling capacity of an SIW structure is primarily determined by its substrate materials and its geometric topology. The power-handling capability depends on the nature of SIW circuits. Usually well-matched traveling-wave circuits can handle much more power than those counterparts with mismatch conditions and resonances (Tarck & Ke, 2013). In the case of filter designs, the SIW cavity resonators are fundamentally responsible for power handling capability in addition to the Microstrip-to-SIW transition (Chen & Ke, 2010; Ke & Chen, 2010).
3. Design analysis of siw component

The SIW parameters must be taken carefully in order to get desired result. The most significant advantage of SIW technology is to integrate all the components on the same substrate with high power-handling capacity as compared to other planar transmission lines i.e. Micro-strip line, strip line, Co-planar line, so there is the possibility to mount one or more chip-sets on the same substrate. SoS (system on substrate) represents the ideal system for cost effective, easy to fabricate and high performance mm-wave systems (Wu, 2006).

The size of the SIW cavity is determined by the corresponding Cut-off frequency (Deslands & Wu, 2002).

\[ f_{c,m,n} = \frac{c}{2\pi} \sqrt{\frac{\mu}{\varepsilon_r}} \left[ \left( \frac{m\pi}{W_{eff}} \right)^2 + \left( \frac{n\pi}{L_{eff}} \right)^2 \right] \]  
(5)

\[ f_{c,1,0} = \frac{c}{2W_{eff}} \sqrt{\frac{\mu}{\varepsilon_r}} \]  
(6)

where, TE\(_{10}\) is the dominant mode. The \( W_{eff} \) and \( L_{eff} \) are the effective width and length of the SIW cavity respectively as shown in Figure 1.

\[ W_{eff} = W - \frac{d^2}{0.95s} \]  
(7)

\[ L_{eff} = L - \frac{d^2}{0.95s} \]  
(8)

where, \( W \) and \( L \) are the actual width and length of the SIW cavity; \( d \) is the diameter of the metal vias; and \( p \) is the distance between adjacent via holes as shown in Figure 8 (Sabri, Ahmad, & Bin Othman, 2012).

For SIW designs, following conditions need to be satisfied

\[ d < \frac{\lambda_g}{5} \]  
(9)

\[ p \leq 4d \]  
(10)

where,

\[ \lambda_g = \frac{2\pi}{\sqrt{\frac{f^2}{c^2} - \left( \frac{f}{w} \right)^2}} \]  
(11)

\( f \) is the operating frequency

\( c \) is the speed of light

The pitch \( p \) must keep small to reduce the leakage loss between adjacent posts. The post diameter may significantly affect the return loss of the waveguide.

4. SIW fabrication techniques

In the frequency range of 60–90 GHz and even at higher frequencies, PCB techniques have been widely used to implement the SIW structures. The PCB fabrication techniques have low manufacturing cost and great design flexibility. In this process, the metal holes are created either by
micro-drilling or by laser cutting and their metallization are performed by using a conductive paste or metal plating (Deslandes, 2003).

At higher frequencies, radiation losses can occur due to some technological limitations. The solution of this problem is that the holes are replaced by metallized slots in the circuit operation (Moldovan, Bosisio, & Wu, 2006). The recent development of LTCC substrate material extends the applicable frequency of the technique up to 100 GHz. The LTCC technology has the advantages of low conductor loss and low dielectric loss. It is very attractive for various integrated packaging.

LTCC provide a harmonic bed for embedded microwave and mm-wave passive components including antennas. LTCC substrate material has a wide tunable range of thermal expansion coefficient (Wu & Huang, 2003). The SIW components were fabricated above 100 GHz by using Photo imageable thick-film materials. In this technique, there are best dimensional tolerances and low dielectric loss (Stephens, Young, & Robertson, 2005).

5. Applications of SIW
The applications of SIW are explained on the basis of passive and active components. The passive components of SIW are filters, circulators and couplers, etc. SIW filters provide good selectivity as compared to other planar filters. The inductive post filter is the simple form of SIW filters as shown in Figure 9 (Deslendes & Wu, 2003).

The zigzag filter topology as shown in Figure 10 (Mira, Mateu, & Cogollos, 2009) includes controllable cross-coupling to provide sharper response.

Figure 9. Inductive post filter.

Figure 10. Zigzag meandered topology

Figure 11. Iris-coupled filter.
The better electrical response provided by the post-wall iris coupled filter is discussed in (Hao, Hong, & Li, 2005; Mira & Bozzi, 2010) as shown in Figure 11.

SIW-based circulator used for high volume and medium power-level applications are shown in Figure 12 (D’Orazio & Wu, 2006; D’Orazio, Wu, & Helszajn, 2004).

Couplers find application in beam forming due to directional property and precision measurement. The most popular coupler is Riblet short-slot coupler which consists of two waveguides with coinciding H-planes and coupler outputs are in phase quadrature. The required output is obtained by the common wall elimination as shown in Figure 13 (Cassivi, Deslendes, & Wu, 2002). The coupler geometry is based on even/odd mode analysis as TE_{10} mode is related to even mode and TE_{20} mode is related for odd mode.

The active SIW components are amplifier, oscillator and mixer, etc. The SIW technology is used in amplifiers for harmonic suppression. Harmonic suppression is achieved by lowering the frequency of second harmonic below cut-off frequency of SIW (He, Wu, & Hong, 2008; Wang & Park, 2012). The block diagram of the SIW amplifier is designed as shown in Figure 14 which consists of two iris-type inductive discontinuities and DC-decoupled transition.

SIW technology can be used to construct high Q resonant cavity. Low-phase noise oscillator could be designed by using high Q resonant cavity. The design concept of these SIW oscillators is shown in Figure 15 (Cassivi & Wu, 2003).
The positive feedback oscillator is the combination of an amplifier and SIW cavity which are formed on the same dielectric substrate. The SIW cavity acts as a frequency selector and the coupling level of the SIW cavity is maintained so that the gain of the loop is slightly greater than 1 dB. The total phase difference of the loop is 0 degree or an integer multiple of $2\pi$ (Barkhausen stability criterion).

6. Conclusion
Over the decades, different types of SIW has been evolved to overcome the bandwidth and size limitations of conventional SIW line. Different topologies have been applied for the size reduction of SIW i.e. Substrate Integrated folded Waveguide (SIFW), Half-mode Substrate Integrated waveguide(HMSIW), Folded Half-mode Substrate Integrated waveguide, and Quadri-folded Substrate Integrated Waveguide. Quadri-folded substrate integrated waveguide will give size reduction of approximate 90% but it will slightly increase the losses. For the bandwidth improvement, two different topologies have been used i.e. Substrate Integrated Slab Waveguide (SISW) and Ridge SIW. Ridge substrate integrated waveguide will give highest mono-modal bandwidth of operation as compared to conventional one. The use of novel material plays an important role for reducing the conductor and dielectric losses of SIW components.

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