Low Loss and High-Power Substrate Integrated Waveguide for High Speed Circuits

Substrate integrated waveguide (SIW) is useful for the propagation of electromagnetic radiation. It inherits the merits of planar transmission lines such as compactness, low weight, planar nature and ease of fabrication and as well as the merits of metallic waveguides such as minimum loss and maximum power handling capability. The following is a review of SIW technology, a design example and a discussion of key characteristics.

mmWave technologies for 5G, 77 GHz automotive radar and 60 GHz gigabit Wi-Fi require waveguide capable efficient transmission. Microstrip and coplanar waveguide can enable desirable form factors, but do not provide ideal performance. Metallic waveguide can operate efficiently at these frequencies; however, waveguide is large, costly, multidimensional in nature and cannot be easily integrated with planar transmission lines.

SIW offers an effective middle ground. In 1998, SIW capable of transmitting electromagnetic waves was developed.[1-2] SIW is a member of the substrate integrated circuit (SIC) family,[3] consisting of substrate integrated slab waveguide (SISW) and substrate integrated non-radiating dielectric (SINRD). SICs are useful for high frequency electronics. SIW is also referred to as post wall waveguide or laminated waveguide. It can be fabricated using PCB technology, low temperature co-fired ceramic (LTCC) technology and photo imaging processes. Along with small size and weight, SIW retains the desirable loss and power handling properties of conventional metallic waveguide. It is used as a transmission medium in high speed circuits, antennas, couplers and dividers.[4]

SIW supports the TE mode of propagation. The absence of TM modes and its inherit structural flexibility makes it promising for filter design. Planar transmission lines such as microstrip or stripline achieve quality factors from 50 to 100, whereas metallic waveguide is in the range of 1000 to 12,000. SIW aims to achieve the intermediate values.[5-6]

SIW Design

Width

SIW is synthesized by embedding two rows of metallic vias on a dielectric substrate with top and bottom metal claddings (see **Figure 1**).[7] Via holes short both the top and bottom copper claddings so that a vertical current path exists. The propagation characteristics of SIW are almost the same as traditional waveguide.[8]

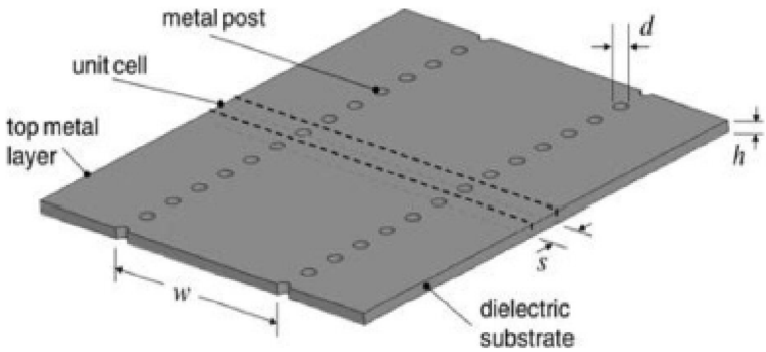

Fig. 1 Substrate integrated waveguide.

The relationship between SIW parameters and the effective width of rectangular waveguide with same propagation characteristics is:[9]

$$w_{eff} = w - d^2 / 0.95\, s \qquad (1)$$

where w is the physical SIW width, d is the diameter of the via hole, s is the center-to-center distance between adjacent vias (pitch) and w_{eff} is the effective SIW width.

SIW width w is obtained from Equation 1 once the effective width is calculated using Equation 2, where c is the velocity of light, fc is the cutoff frequency of the dominant TE_{10} mode and εr is the substrate permittivity.

$$w_{eff} = c / (2fc \text{ sqrt } (\varepsilon_r)) \qquad (2)$$

Equation 1 does not take the effect of d/w into account. Hence, a more accurate relationship is:[10]

$$w_{eff} = w - 1.08\, d^2 / s + 0.1\, d^2/w \qquad (3)$$

Another empirical relation based on the method of lines (MOL) is:[11]

$$w_{eff} = w \times (\xi_1 + \xi_2/(s / d + (\xi_1 + \xi_2 - \xi_3))/(\xi_3 - \xi_1)) \qquad (4)$$

Where:

$$\xi_1 = 1.0198 + (0.3465/ (w / s - 1.0684)) \qquad (5)$$

$$\xi_2 = - 0.1183 + (1.2729/ (w / s - 1.2010)) \qquad (6)$$

$$\xi_3 = - 1.0082 + (0.9163/ (w / s + 0.2152)) \qquad (7)$$

Vias

The design parameters of the via holes must satisfy the conditions:[12]

$$d < \lambda_g/5 \qquad (8)$$

$$s < 2d \qquad (9)$$

The pitch must be as small as possible to minimize radiation leakage. To eliminate band gap effect and ensure mechanical rigidity the SIW should satisfy:[9]

$$0.05 < s / \lambda_c < 0.25 \qquad (10)$$

SIW Parameters

SIW impedance Z_0, can be computed from:

$$Z_0 = (h / w_{eff})\ (\eta / \mathrm{sqrt}\ (1- (\lambda/ \lambda c)^2) \qquad (11)$$

where free space wavelength and cutoff wavelength are denoted by λ and λc respectively, and:

$$\eta = 120\pi / \mathrm{sqrt}\ (\varepsilon_r) \qquad (12)$$

The phase constant β is calculated for a low loss tangent dielectric material:

$$\beta = \mathrm{sqrt}\ [(2\pi f\ \mathrm{sqrt}\ (\varepsilon_r)/300)^2 - (\pi/ w_{eff})^2] \qquad (13)$$

Here, frequency f is represented in GHz and effective width w_{eff} in mm.

Simulation

A SIW is designed on a double-sided copper clad Rogers 6002s substrate with dielectric loss equal to 0.0012 and a permittivity of 2.94. The basic dimensions are calculated using Equations 1 through 10. The structure in **Figure 2** is simulated using CST-Microwave studio. **Table 1** lists the dimensions.

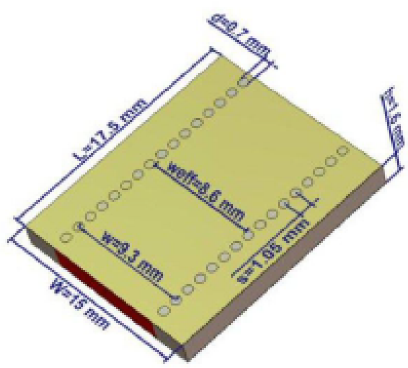

Fig. 2 Perspective view of the SIW structure.

Table 1 SIW DIMENSIONS

Parameter	Symbol	Value (mm)
Substrate width	W	15
Substrate length	L	17.5
Substrate height	h	1.6
Via diameter	d	0.7
Spacing(pitch)	s	1.05
SIW width	w	9.3
Effective width	w_{eff}	8.6

S-parameters of the SIW (see **Figure 3**) show a cutoff frequency of 11 GHz with a minimum pass band insertion loss and an in-band return loss greater than 10 dB.

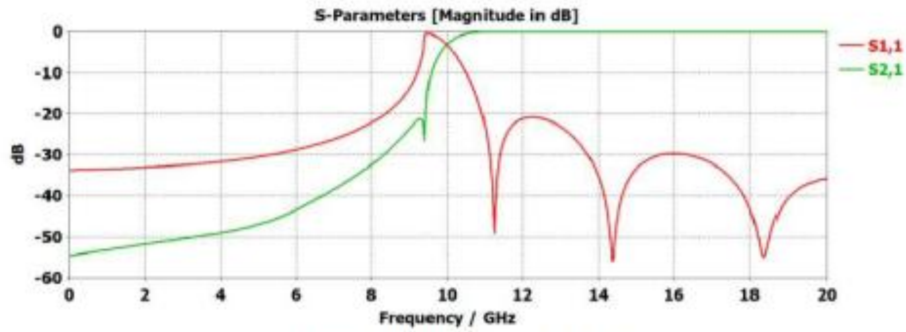

Fig. 3 SIW S-parameters.

Figures 4 and **5** represent the electric field distribution of the structure at 11 and 20 GHz, respectively. It is evident that the field is bounded within the SIW vias.

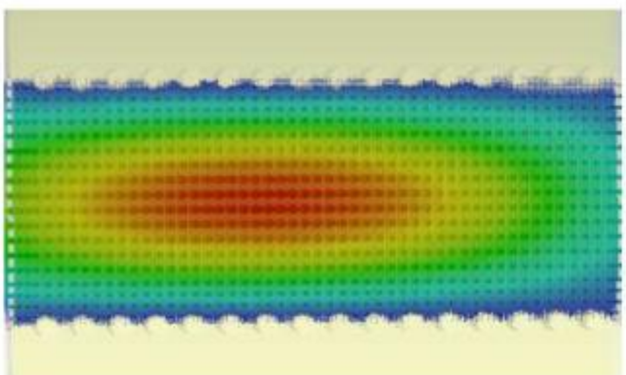

Fig. 4 E-Field at 11 GHz.

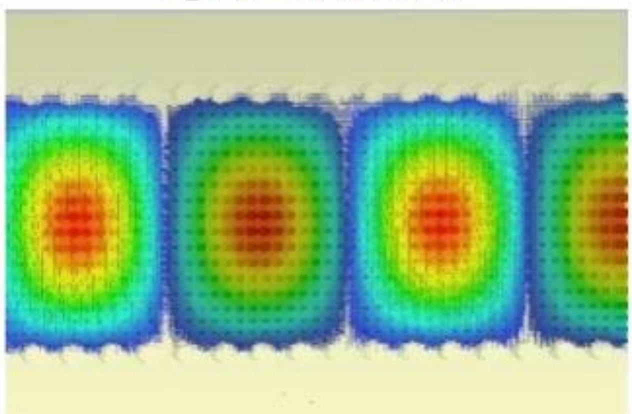

Fig. 5 E-Field at 20 GHz.

The SIW impedance and phase constant are calculated using Equations 11 through 13. The variation of SIW impedance for different dielectric constants (with constant effective width 8.6 mm) and different effective widths (with constant dielectric constant of 2.94) is shown in **Figures 6** and **7**, respectively. It is inferred from Figure 6 that impedance is inversely proportional to the dielectric constant for constant w_{eff}. Also, Figure 7 shows that impedance is inversely proportional to effective width for a constant ε_r.

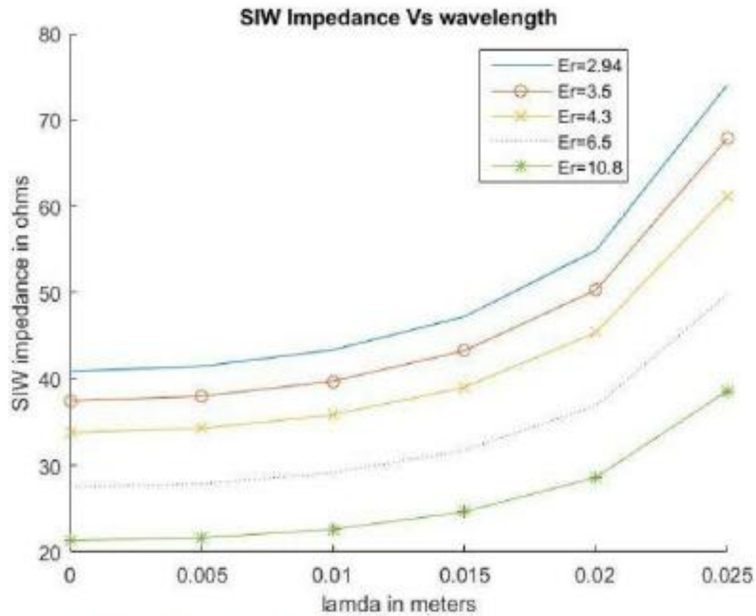

Fig. 6 Variation of SIW impedance for various ε_r.

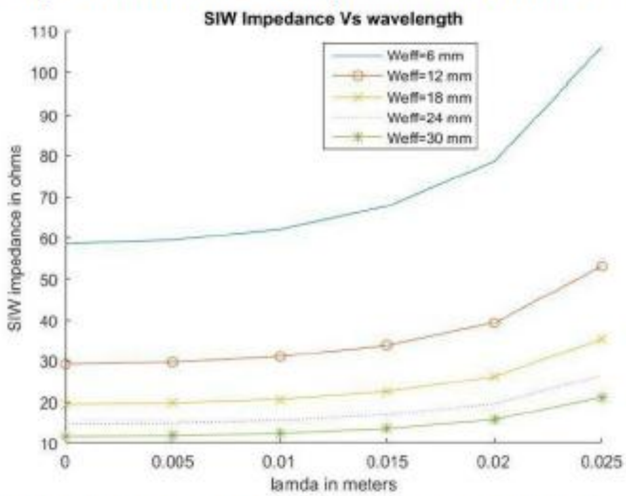

Fig. 7 Variation of SIW impedance for various w_{eff}.

Analysis of the SIW phase constant for different dielectric constants (with constant effective width 8.6 mm) and different effective widths (with a constant dielectric constant of 2.94) is shown in **Figures 8** and **9**, respectively. From Figure 8, the phase constant increases with increasing dielectric constant. Figure 9 shows that the phase constant is independent of effective width.

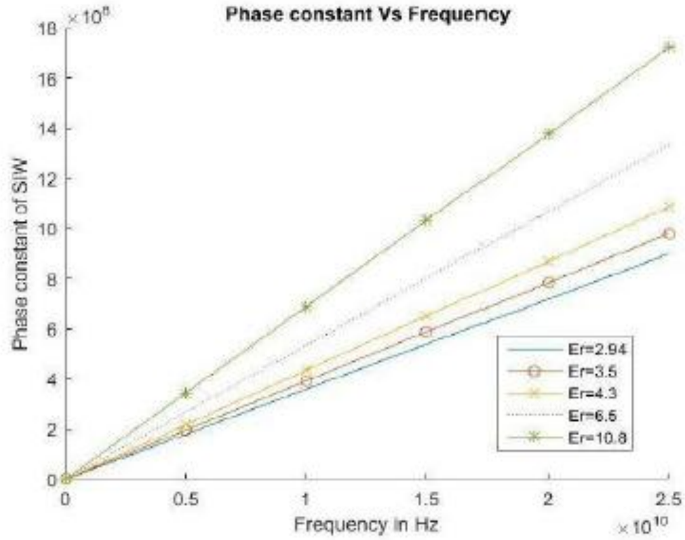

Fig. 8 Variation of SIW phase constant for various ε_r.

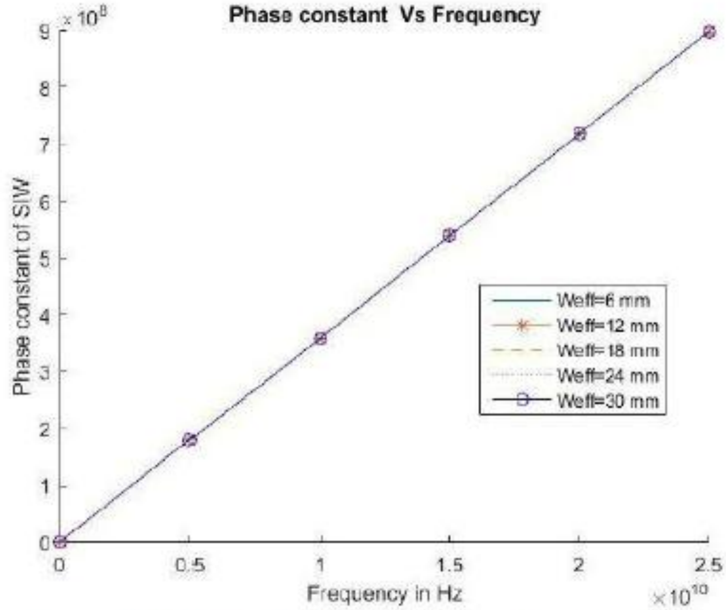

Fig. 9 Variation of SIW phase constant for various w_{eff}.

Conclusion

A theory for the design of SIW is developed. A SIW with a cutoff frequency of 11 GHz is designed using CST-MWS. S-parameters show a sharp cutoff at 11 GHz. The electric field is confined within the SIW vias and there is no leakage. SIW characteristics such as impedance and phase constant analyzed using MATLAB show that impedance is inversely proportional to dielectric constant and effective width of equivalent waveguide, whereas the phase constant is directly proportional to the dielectric constant and independent of effective width of equivalent waveguide. SIW characteristics make it a suitable candidate for miniaturized, low loss, high power handling planar components.