Modelling, Design and Parametric Considerations for different Dielectric Materials on Substrate Integrated Waveguide

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Abstract- In this paper, the model of substrate integrated waveguide (SIW) has been analyzed and designed to investigate the effect of dielectric materials on its operating parameters. Parameters that have been evaluated in this work are electric field, return losses and the transmission gain. Printed circuit board (PCB), silicon (Si), Mica and polymethyl methacrylate (PMMA) are used as different dielectrics to evaluate the results in the frequency domain of 1 to 10 GHz. Design steps in an orderly manner were pursued for the optimization of geometrical dimensions followed by the finite-element method (FEM) based modeling of the SIW structure. The results obtained had shown that the maximum change in the electric field is observed for PMMA while the transmission gain increases with the increase in frequency up to 9.75 GHz and correspondingly the return loss is minimum at this frequency.

Keywords- Substrate integrated waveguide, finite element method, return loss, dielectric filled waveguide, transmission gain, electric field.

1 Introduction

In recent years, development in the field of small integrated radio frequency (RF) systems led the scaling of waveguides to micron level. These devices are being develop and optimized which can be manufactured and integrated within RF circuits [1]. Dielectric waveguides are the fundamental building blocks of integrated circuits. Apart from being a transmission medium to confine and directing signals, they can be used as the basis for circuits such as filters and directional coupler [2]. Conventional waveguides structures had the advantages of having high power carrying capacity and high Q-factor, but also had the disadvantages of being bulky, heavy, and unsuitable for low-cost mass production techniques [3]. This led to the exploration of new innovative small scale waveguides. The millimeter (mm) wave technology is an important tool for the fabrication of small integrated RF system. Broadband and high resolution techniques are supported by the use of mm-waves [4]. Successful development of mm-wave wireless systems requires high performance, low-cost and reliable technology. Substrate integrated waveguide (SIW) technology is promising candidate for developing mm wave devices [5].

2 Substrate Integrated Waveguide

SIW are integrated waveguide. The basic structure of SIW consists of two rows of conducting slots created in a dielectric substrate [6]. These slots electrically connect two parallel metal plates as shown in Fig. 1.

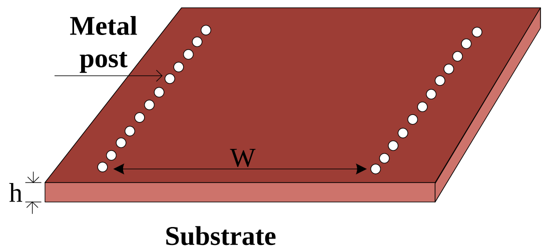

Fig. 1 Schematic geometry of a SIW

SIW is one of the forms of dielectric filled waveguide (DFW). Thickness of the substrate does not affect the cut off frequency. Therefore the substrate can be at any thickness. The dielectric loss is inversely proportional to the thickness of substrate [7]. The design formulas of the SIW are given by first defining the width of the substrate (shown in Fig. 2) such as

$$a_d = \frac{a}{\sqrt{\varepsilon_R}}$$

The distance between opposite via of the SIW is given by [8]

$$a_s = a_d + \frac{d^2}{0.95p}$$

Where d is the diameter of the via, p is pitch (distance between the vias)

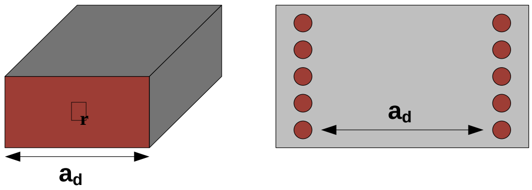

Fig. 2 Dimensions for DFW and SIW

The guided wavelength in the SIW is given by following formula [9]

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_R (2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}}$$

SIW waveguides propagation characteristics are similar to classical rectangular waveguides [10]. Also field pattern and the dispersion characteristics are same. Apart from these similarities, SIW structure has high Q-factor and high power-handling capability with self consistent electrical shielding which are the merits of these structures over conventional metallic waveguide [11].

3 Design and Analysis

Figure 3 shows the structure of an SIW consisting of the top and bottom metal planes of a substrate and two parallel via fences in the substrate. The via are composed such that only patterns with vertical current distributed on the side wall can survive in SIWs.

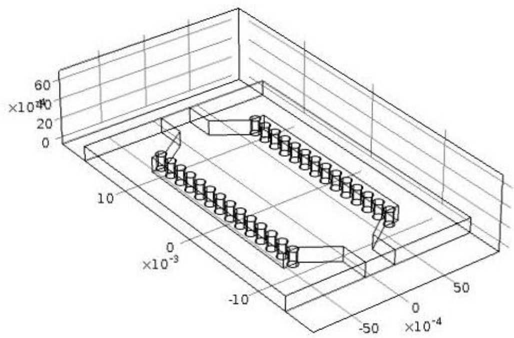

Fig. 3 Structure of designed SIW

The current path will not be cut by via fences, therefore TE_{10} mode can be supported in an SIW. This holds for all TE_{m0} modes since their current distributions on the side walls are similar. On the other hand, horizontal components of the surface current exist on the sidewalls for all TM modes and TE_{mn} modes with nonzero n's. These current paths will be cut in SIW structures, which results in radiation. Therefore we can conclude that only TE_{m0} modes exist in SIW structures [12]. Properties of TE_{m0} modes are listed in Table 1.

Table 1. Properties of rectangular waveguide in TE_{m0} mode

Property	TE_{m0} mode
Generating function	$\psi_{m0} = \cos m\pi x / a$
Cut off wave number	$k_{c,m0} = m\pi / a$
Propagation constant	$\chi_{m0}^2 = k_{c,m0}^2 - k^2$, $k = \omega\sqrt{\mu\varepsilon}$
Magnetic field	$\bar{H}_t = \pm\chi_{m0}\nabla_t\psi_{m0}e^{\pm\chi_{m0}z}$, $H_{z,m0} = k_{c,m0}^2\psi_{m0}e^{\pm\chi_{m0}z}$
Electric field	$\bar{E}_t = \pm Z_h \hat{a}_z \times \bar{H}_t$, $Z = j\omega\mu_0 / \chi = jk_0\eta / \chi$
Power flow	$ab\eta k\beta_{m0}k_{c,m0}^2 / 4$

Different substrates have been taken for this experiment to find their effect on the propagation patterns of SIWs. Table 2 shows different materials taken as substrate along with their properties.

Table 2. Properties of different dielectric materials taken

Materials	Relative Permittivity	Relative Permeability	Electrical Conductivity
PCB	3.38	1	0
Silicon	11.7	1	1×10^{-12}
PMMA	3	1	1×10^{-19}
Mica	6	1	2×10^{-15}

The models were designed using electromagnetic, frequency domain solver. Frequency of 11 GHz is applied through the lumped ports to analyze the results for different SIW designs.

4 Results and Discussions

Fig. 4 shows the meshing design of a micro-cantilever model. Normal meshing is conducted on the SIW structure. The maximum element size selected is 0.00375. The design was simulated on the computational machine having 3.4 GHz processor speed. The virtual memory used while simulation was 2.97 GB. Normal meshing is selected to reduce the computational load.

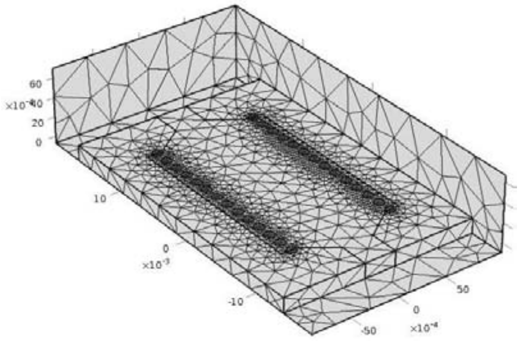

Fig. 4 SIW structure while meshing is applied.

The electric field generated while computing the results for different substrates are shown in figure 5. Fig. 5(a) shows the simulated result for electric field for PCB as substrate, while fig. 5(b), 5(c) and 5(d) shows the radiations due to electric field generated for substrates taken as Silicon, Mica and PMMA respectively.

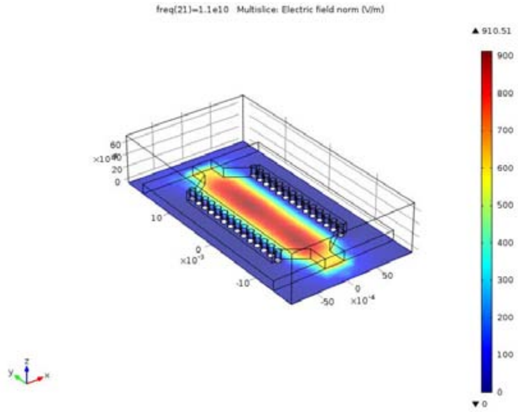

Fig. 5(a) Electric field for PCB substrate

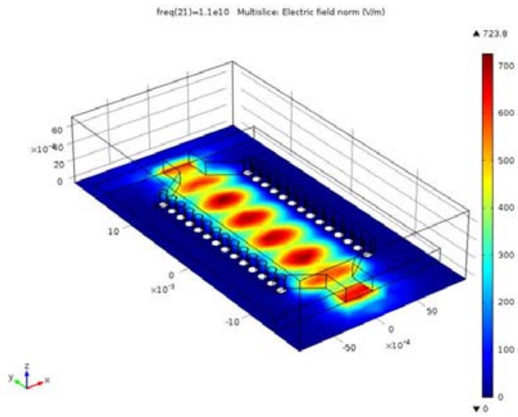

Fig. 5(b) Electric field for silicon substrate

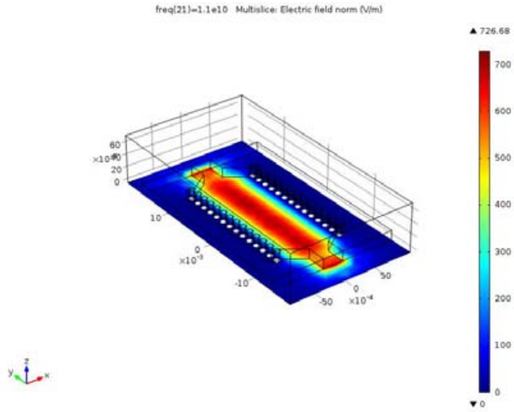

Fig. 5(c) Electric field for Mica substrate

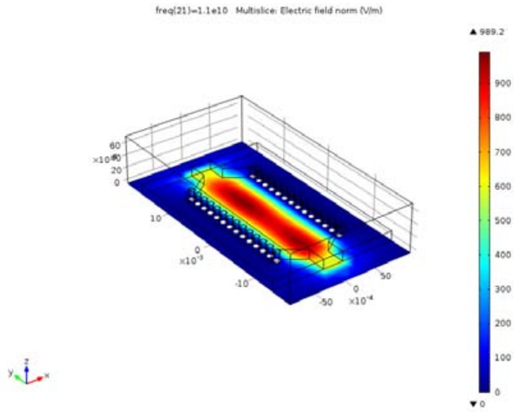

Fig. 5(d) Electric field for pmma substrate

From the bar line adjacent to these graphs it is clear that the maximum value (989.2 V/m) of electric field is for PMMA while for minimum value (723.8 V/m) is for silicon. For PCB and Mica, the maximum value of electric field is 910.51 V/m and 726.68 V/m respectively.

Similarly the plot shown in figure 6 indicates graph between S-parameters and the frequency. Return losses or input reflection coefficient (S_{11}) and the forward transmission gain (S_{21}) were plotted for all the dielectric material used as a substrate in the experiment.

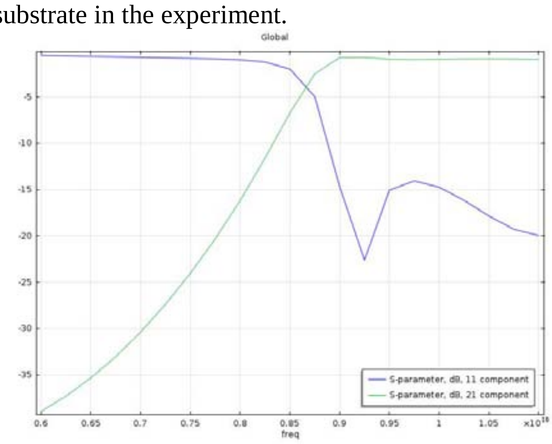

Fig. 6 (a) PCB substrate

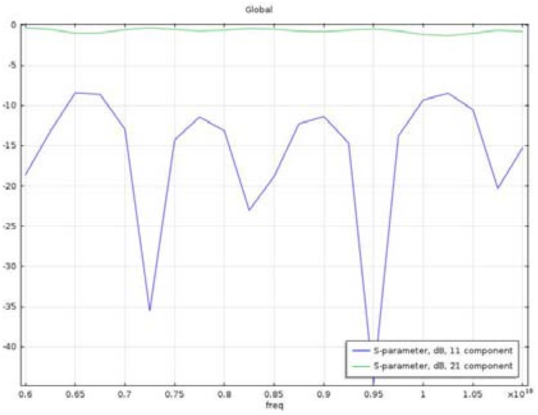

Fig. 6(b) Silicon substrate

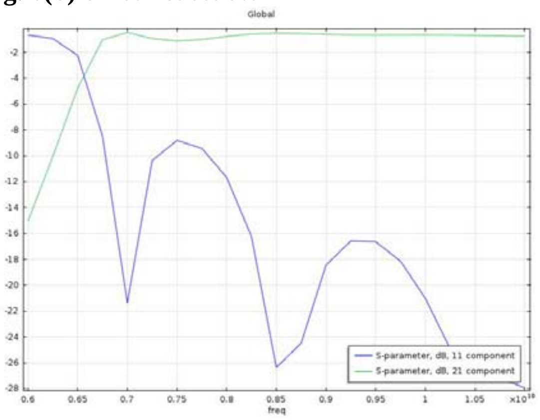

Fig. 6(c) Mica substrate

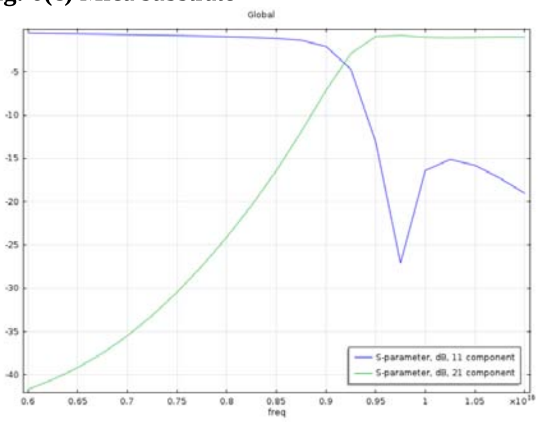

Fig. 6(a) PMMA substrate

Fig. 6(a) shows the S_{11} and S_{21} parameter w. r. t. frequency plot for PCB. Dip in the return loss is observed at 9.25 GHz and transmission gain increases upto 9 GHz and then saturates. Similarly, return loss and transmission gain for silicon, mica, and PMMA are also plotted from Fig. 6(b) to 6(d). In case of silicon return loss showed a wide range variation i.e. various dips are seen at frequencies 7.25, 8.25, and 9.5 GHz, while transmission gain is unity. Similar parametric curve for return loss and transmission gain is observed in case for mica as substrate. Return loss is almost unity after 7 GHz frequency and transmission gain shows dips of -21dB, -26dB, and -28dB at frequencies 7 GHz, 8.5 GHz, and 10 GHz respectively. PMMA polymer substrate used in the simulation showed increase in the transmission gain upto a frequency from 6 GHz to 9.5 GHz. Unity transmission gain is obtained from 9.5 GHz to 11 GHz. Dip in the return loss of -27dB is seen at frequency of 9.75 GHz.

5 Conclusion

Simulated experiment work is carried out to investigate the effect of different dielectric substrates on the electromagnetic wave propagation in SIW. To evaluate the effect of dielectric material, four different substrates such as PCB, mica, silicon, and PMMA were used in the experiment. S-parameters such as return loss and transmission gain were calculated for frequency ranging from 6 GHz to 12 GHz. It can be concluded that the SIW works efficiently at around 9 GHz. For PMMA and PCB, the result evaluations are found to be better than the Si and Mica as dielectric substrates.

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