Filter Antenna Module using Substrate Integrated Waveguide

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Abstract— This paper presents the method for integrating the substrate integrated waveguide and microstrip rectangular patch antenna on a single substrate to produce filtering and radiating element in a single module. The integrated microwave filter and antenna at center frequency of 2GHz has been designed and simulated on HFSS simulation tool.FR4 is used as a substrate having dielectric constant of 4.6.By simulating the integrated Antenna-Filter main lobe magnitude of 6.10dB is obtained. The integration of the antenna and filter into just one module leads to reduction of size, weight in RF front end.

Key words: Substrate Integrated Waveguide, Band Pass Filter, Patch Antenna, High Frequency Simulation Structure

I. INTRODUCTION

The central theme of this paper is to design compact Substrate Integrated Waveguide bandpass filters and rectangular microstrip patch antenna separately and combined both filter and antenna in single module with the help of 50Ω microstrip line. Comparative study and analysis of Integrated Filter-Antenna have been carried out in this paper.

Waveguide can be used to design high frequency components but requires complex transitions to integrate planar circuits. Several studies of transitions between microstrip line and rectangular waveguide have been reported [1]–[4].However, typical integration schemes from rectangular waveguide with planar structure are bulky and usually require a precision machining process, which is difficult to achieve at millimeter-wave frequencies for mass production. To overcome the disadvantages of waveguide Substrate Integrated Waveguide has been introduced. SIW are also known as Post Wall Waveguide (PWWG). A PWWG is a waveguide transmission line that can be embedded in a PCB. Rows of cylindrical posts constitute the side walls and together with an optional top and bottom plate they enclose a rectangular cross section similar to the waveguide. The posts can be either conducting (metallic posts) or insulating (dielectric posts with a permittivity different from the background medium). This emerging guided-wave structure can be made with a pair of periodic metalized via arrays or slot trenches and it looks like two parallel fences that have a specific spacing in which EM waves are well confined.

SIW structures preserve most of the advantages of conventional metallic waveguides, namely high quality-factor and high power-handling capability with self-consistent electrical shielding. The most significant advantage of SIW technology is the possibility to integrate all the components on the same substrate, including passive components, active elements and even antennas.

II. THEORY AND DESIGN OF SIW BPF

A. SIW:

The SIW scheme belongs to the family of SICs in which any other non-planar structures such as dielectric waveguides and coaxial lines can also be made in planar form [8]. Since the truncated side walls do not allow longitudinal current flow, the SIW structure only supports the propagation of quasi transverse electric (TE) modes that have properties similar those in a conventional metallic waveguide. In most cases, only the TE_{m0} modes are of interest because the substrate thickness is relatively thin with respect to the SIW width (at least twice). If generated or existing along the structure, transverse magnetic (TM) modes will immediately become leaky through unbounded via windows along the transversal direction.

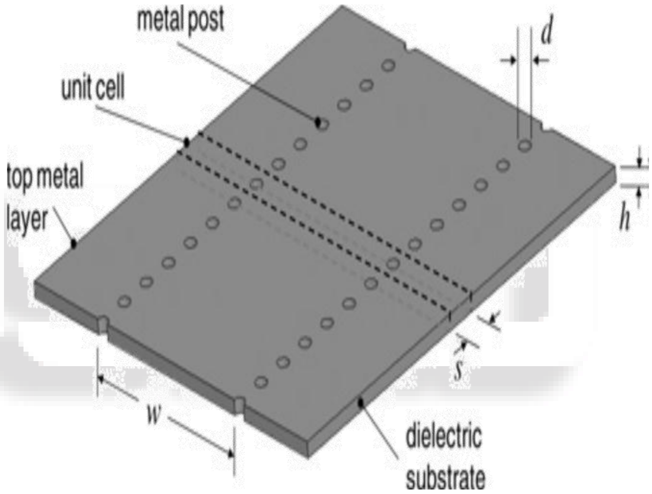

Fig. 2.1: Substrate Integrated Waveguide

Various wave guidance and leakage characteristics of the SIW were discussed in detail in [2] and [3]. In the design of SIW components, one must ensure that the SIW operates in the frequency band of interest where there are no bandgap effects and leakage loss is negligible over the entire waveguide bandwidth of interest. When the period length increases, the EM field may no longer be confined within the two arrays of via cylinders. Part of the energy may also propagate outside the two rows of cylinders, thus resulting in leakage losses. The bandwidth of the bandgap increases when the diameter of the cylinder decreases. The TE_{10} mode related frequency region of interest is defined by

$$p > d \quad (2.1)$$

$$p < \lambda_c 0.25 \quad (2.2)$$

$$a_1 / k_0 < 10^{-4} \quad (2.3)$$

Where p is the pitch, d is the diameter of vias, a_1 is the total loss and k_0 is the wave number in free space.

B. SIW Band Pass Filter:

In this paper, a development of rectangular SIW filter based on microwave filter circuit theory is presented. The rectangular SIW filter is designed at resonant frequency of 2

GHz for single-mode on FR4 substrate having substrate thickness of 1.6mm with loss tangent of 0.0019.

For designing a Band Pass filter, low-pass prototype equivalent circuit is used to produce single-mode SIW filter as shown in Fig.2.2. Impedance Inverters are used as a coupling circuit between input and output ports of filter.

Input and output ports are matched with 50ohm microstrip line at ports. The value of LP prototype using generalized equations are given in table 2.1.

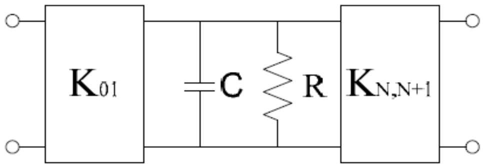

Fig. 2.2: Low equivalent circuit

g1	g2	g3	g4	g5	g6
0.7563	1.3049	1.5773	1.3049	0.7563	1

Table 2.1: Normalized values for low pass filter prototype

For designing band pass filter firstly low pass filter is designed and then it is transformed into band pass filter. Insertion loss method is used for designing band pass filter. Low pass prototype is designed by using Chebyshev low pass filter design approximations. The general equation of the transformation process from low pass to band pass is given below in Eq.(2.4).

$$\omega' = \frac{\omega_0}{\omega_2 - \omega_1}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \qquad (2.4)$$

Where ω' = normalized angular frequency, ω_0=central angular frequency of BPF and is equal to $2\pi f_0$ where f_0=2GHz, ω_2-ω_1 is bandwidth of the band pass filter. $\omega_2 = 2\pi f_2$ where f_2=2.5GHz and $\omega_1 = 2\pi f_1$ where f_1=1.5GHz. The series inductor L are converted into series inductor L_s and capacitor C_s and parallel capacitor C is converted into parallel inductor L_p and capacitor C_p by using the following Eq. (2.6) and Eq.(2.7).

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \qquad (2.5)$$

$$L_s' = \frac{L_k Z_0}{\omega_0 \Delta}, \qquad C_S' = \frac{\Delta}{L_k Z_0 \omega_0} \qquad (2.6)$$

$$L_P' = \frac{\Delta Z_0}{\omega_0 C_k} \qquad C_P = \frac{C_k}{\Delta Z_0 \omega_0} \qquad (2.7)$$

The SIW filter is an artificial waveguide which is constructed on a planar structure with arrays of metalized via holes inside the cavity. SIW filter is applied based on the rectangular waveguide concept so that it can be integrated with any planar structure.

L1(nH)	L2(nH)	L3(nH)	L4(nH)	L5(nH)	L6(nH)
6.02	1.5246	12.55	1.5246	6.02	1.99
C1(pF)	C2(pF)	C3(pF)	C4(pF)	C5(pF)	C6(pF)
1.52	4.153	0.504	4.15	1.052	3.183

Table 2.2: Capacitor and Inductor Values

The design rules for the rectangular SIW based upon TE_{mnt} are determined by the resonant frequency.

$$f_r(mnt) = \frac{v_c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{m\pi}{a_{eff}}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{t\pi}{l_{eff}}\right)^2} \qquad (2.8)$$

Where m, n and p are the mode of indexes for TE_{mnt} mode; v_c is the free space velocity of the light; while the effective length l_{eff}, b and effective width, a_{eff} are the dimension of the SIW cavity.

$$a_{eff} = a_{SIW} - \frac{d^2}{.95p} \qquad (2.9)$$

$$l_{eff} = l_{SIW} - \frac{d^2}{.95p} \qquad (2.10)$$

Where, l_{SIW} and a_{SIW} are the length and width of the resonant SIW cavity, d and p are the diameter and the distance between adjacent vias respectively. μ_r and ε_r are the relative permeability and the dielectric constant of the substrate respectively.

The specification for the design of 5th order substrate integrated waveguide filter has been given below:
Height of substrate h = 1.6mm,
Dielectric Substrate = Epoxy FR4
Dielectric Constant ε_r = 4.6,Cut off frequency f_0=2GHz
Width of SIW a = 51.62mm, Length of SIW b=49.3505mm
Diameter of vias d = 1mm, Spacing between vias p = 3mm

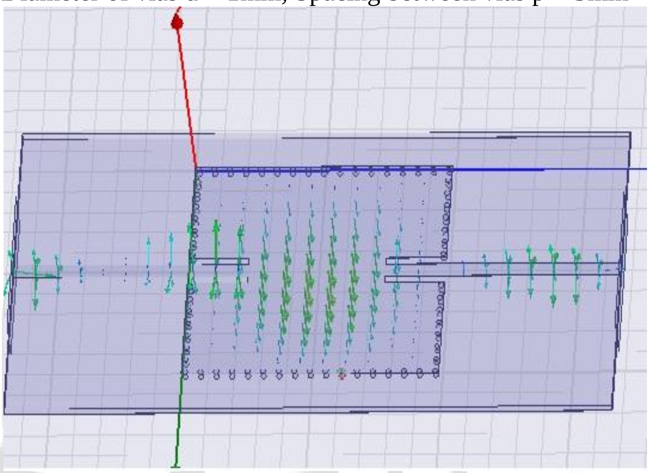
Fig. 2.3: E-field distribution of rectangular SIW filter in single mode at centre frequency of 2 GHz

Substrate Integrated Waveguide has been design and simulated on Ansoft HFSS 14.0 simulation software. The SIW simulation diagram has been shown in the Fig. 2.3.Here the center couple SIW filter has been designed using inset fed coupling.TE_{10} is dominant mode working in SIW filter. Where m=1 and n=0,one means one half cycle in + y direction. In this design the diameter of the post and the distance between them are chosen properly, so that energy leaking between consecutive posts is negligible. The electric field for the TE_{10} mode on SIW filter at 2 GHz is shown in Fig.2.3. The simulations show the magnitude of E field is concentrated in the center of the SIW cavity. In this situation, the array of via-holes of the SIW is used as a boundary to prevent the electromagnetic fields escaping from the SIW cavity.

Maximum return loss and minimum insertion loss are obtained respectively as -28.8025dB -0.3999dB at 2GHz.SIW filter shows a narrowband characteristics. Curve shows the bandwidth of 40MHz at 10dB of attenuation. The two metallic plates used above and below of the dielectric substrate are made of copper and having thickness of 0.035mm.

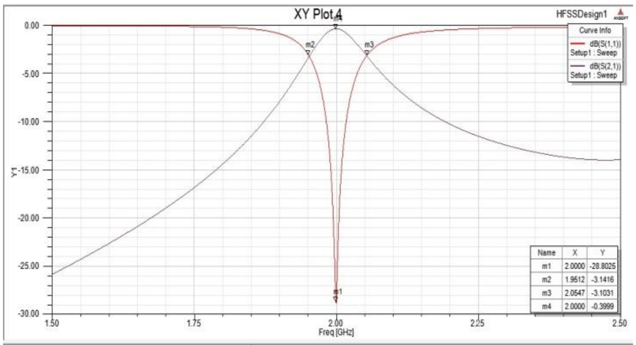

Fig. 2.4: Return Loss and Insertion loss graph at 2GHz cut off frequency

III. RECTANGULAR PATCH ANTENNA

In the typical design procedure of rectangular Microstrip patch antenna, three essential parameters are frequency of operation, dielectric constant, substrate height. For designing microstrip patch antenna the designing specification are as follows:

Parameters	Value
Cut off frequency(f_r)	2GHz
Substrate used	Epoxy FR4
Dielectric constant($\in_r$)	4.6
Patch Width(W)	38 mm
Effective Dielectric Constant($\in_{rr}$)	4.3
Actual Patch Length(L)	34.67 mm
Inset Gap	2.959 mm
Inset Length	12.569 mm

Table 3: patch antenna the designing specification

Epoxy FR4 is a high-quality substrate composed of uniformly dispersed glass microfiber in a PTFE matrix. It provides a microscopically-controlled, uniform relative permittivity of 4.6 ±0.02 and a loss tangent of 0.0019 of claddings. A substrate thickness of 1.6 mm, the largest off-the-shelf thickness available, was chosen to increase the bandwidth and reduce dielectric losses. At a frequency of 2GHz, the ratio of substrate thickness to free-space wavelength h/l0 is 0.025. The cut-off frequency for higher-order surface-wave modes is far above 2GHz; therefore, surface-wave losses should be negligible for this substrate. Inset fed technique is used for providing source of excitation. By designing the patch antenna with given design parameter on Ansoft HFSS simulation software.

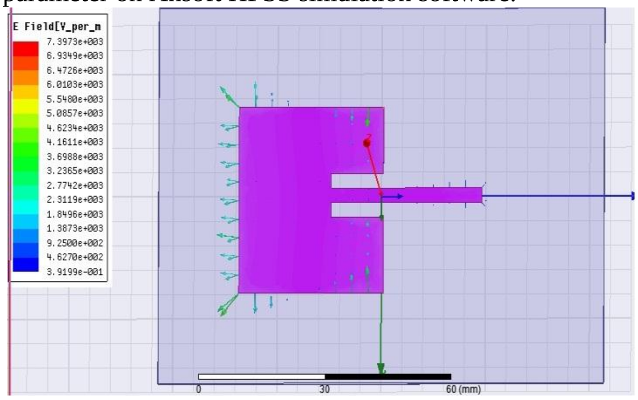

Fig. 3.1: E-Field distribution in rectangular patch antenna

As the figure shows that the radiation emitted from the width side only and electric field vector will cancel out from the remaining side.

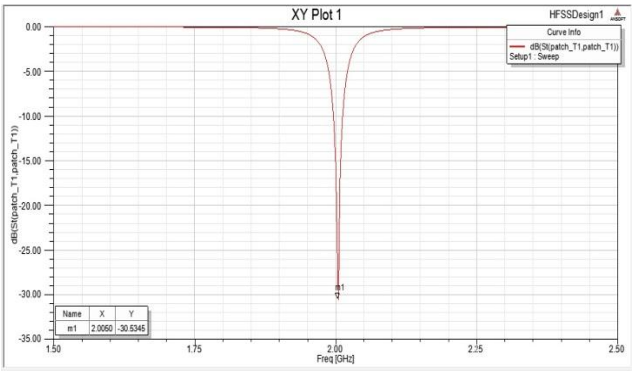

Fig. 3.2: S_{11} graph for inset fed rectangular patch antenna

The swept S_{11} indicates a maximum return loss of -30.5345 dB at 2GHz resonant frequency. The swept VSWR curve for the range 1.5 to 2.5 GHz is shown in Figure 3.2 and indicates a bandwidth of 26 MHz, over which the VSWR is less than 2:1. Rectangular Microstrip patch antenna shows a peak gain of 6.59dB and peak directivity of 7.206dB.This antenna shows a radiation efficiency of 86.7%.

IV. INTEGRATED FILTER ANTENNA

Integrated filter antenna are designed on same substrate FR4 having thickness of 1.6mm.Copper is used as material for two layers of metallic plates in substrate integrated waveguide filter. Bottom layer is used as ground for both the SIW and microstrip patch antenna. Top layer of copper in SIW are used to confine the EM wave in between the substrate. Poles or vias in SIW filter are internally metallized with copper. The integrated filter antenna module is designed on Ansoft HFSS software as shown in the Fig. 4.1.

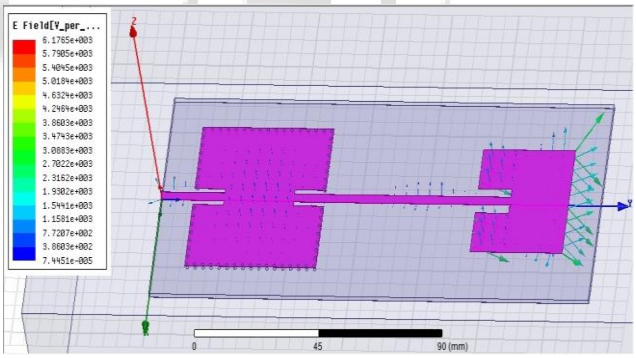

Fig. 4.1: E-field distribution for integrated rectangular SIW filter and rectangular microstrip patch antenna in single mode (TE_{10}) at 2GHz.

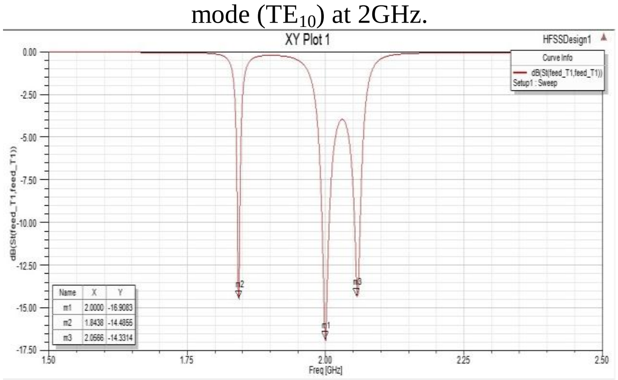

Fig. 4.2 Simulated results of integrated rectangular SIW filter and rectangular microstrip patch antenna designed at 2 GHz.

The simulated response for the integrated filter and antenna is shown in Fig. 4.2. The return loss (S11) of -16.9083 dB and bandwidth of 21MHz are achieved especially in the passband.Fig.4.2 shows that integrated filter antenna shows three resonant frequency. So this filter antenna can work as multi band antenna. The three resonant frequencies are 1.8438GHz,2GHz and 2.0566GHz. Respective return losses for resonant frequencies are -14.4885dB,-16.9083 and -14.3314dB.

V. CONCLUSION

A new design of integrated rectangular SIW filter with rectangular microstrip patch antenna has been successfully designed at 2GHz cut off frequency on FR 4 substrate and return loss has been measured on Ansoft HFSS simulation software. The study can be further explored by developing the prototype of multilayer integration between the rectangular SIW filter and rectangular microstrip patch antenna in order to significantly reduce the overall physical volume. The integrated microwave filter and antenna is useful for any transceivers in RF/ microwave front-end subsystems particularly where the reduction of overall physical volume and cost is very important.

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