A Novel Structure of Multilayer SIW Filter and Patch Antenna

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***Abstract*—This paper presents the investigation based upon the resonant circuit approach to distinguish in between the microwave filter and antenna from the equivalent circuit to physical layout where this system is used to reduce the overall volume of RF front-end subsystem especially in wireless communication systems. The physical layouts of the Substrate Integrated Waveguide (SIW) filter and microstrip patch antenna based on single-mode is established based on multilayer technique. This study focuses on the integrated rectangular SIW filter with rectangular microstrip patch antenna to produce radiating and filtering system in a single device. To prove the concept of microwave filter and antenna, the operating centre frequency of 2 GHz is demonstrated and validated through simulation and measurement. The experimental shows promising results and in-line with the simulated results. This study is useful for any microwave system design where the reduction of overall physical volume and weight as well as cost is very important such as in base stations.**

Keywords-Resonant Circuit, Integrated Microwave Filters and Antenna, Substrate Integrated Waveguide, Microstrip Patch Antenna, Multilayer Technique

I. INTRODUCTION

In wireless communication systems, most of the applications are diverse, as in through satellite television as well as into public and military radar systems. In the field of communications, cellular radio is becoming more important in comparison to conventional telephones [1]. In most communication systems the receiving antenna is accompanied by a bandpass filter shown in Fig. 1. In the microwave band, normally the receiving bandpass filters or waveguide filters are distributed. These filters are not compact and in most applications their size becomes an issue and as such may not provide a good solution.

Many researchers have taken this into account to invent an alternative solution for the better communication device that able to reduce the overall size and cost of the end user [2]-[11]. However, most of the wireless communication applications require better performance in term of reliability, simple and small in size of the filter and antenna that can be implemented in a single device. Basically, filters and antennas are designed separately which have been connected using an external impedance as connection in between of it. In order to obtain better performance, both filter and antenna need perfectly matched by using a suitable impedance matching for both devices.

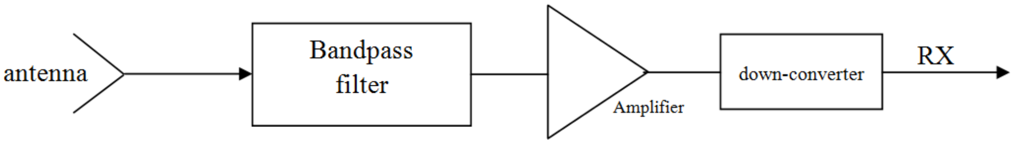


Fig.1. Typical block diagram of receiving front end communication system

In modern wireless communication systems, filters and antennas design are needed both in mobile phones and at the base station. A typical block diagram of the RF front end of a cellular radio base station is shown in Fig. 2. However, there is a growing interest for integration of microwave filter and antenna in wireless communication systems using various methods. There are some methods have been proposed in [5]-[14] to realize the integration technique for filter and antenna. However, the method applied for the integration in [12],[13] using slots are difficult to realize due to its meandered slots structure and thus the design become more complex. In [14] the filter and antenna was designed using a multilayer structure with coupling slot and coaxial feeding methods was used on the both elements for the integrated design. However, the structure increases the overall size of physical layout, weight and manufacturing cost. Recently, [5] has proposed co-design of a compact dual-band filter-antenna for WLAN application. The integration concept uses a loop-load dual-band monopole radiator and dual-band pseudo-interdigital bandpass filter for microstrip structure. This design provides good selectivity and rejection in out of band region. However, the filter - antenna structure is quite complex to design due to the interdigital structure that requires a symmetric slot.

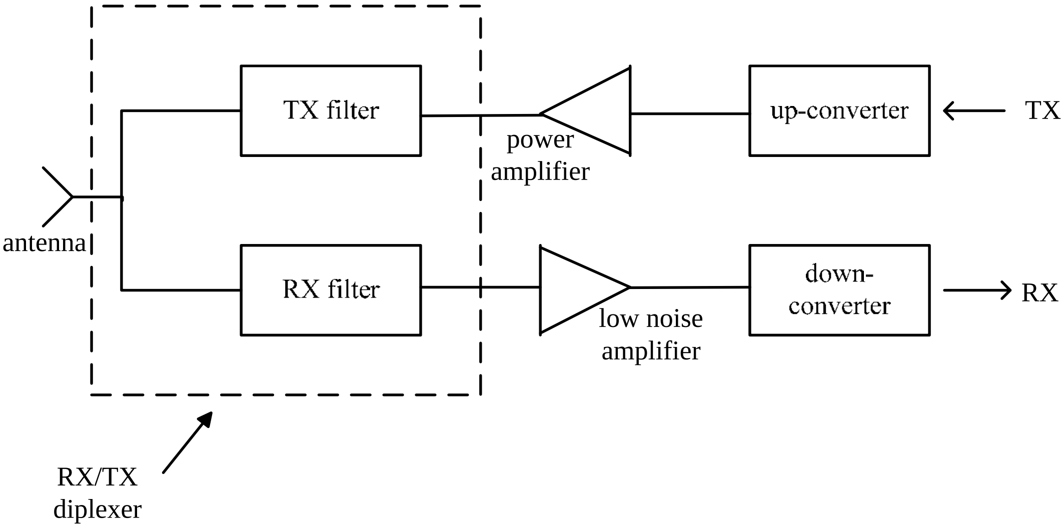


Fig.2. Block diagram of the RF front end of wireless communication systems in the base station

In this paper, a development of rectangular SIW filter and rectangular microstrip patch antenna based on microwave filter circuit theory is presented. The rectangular SIW filter and rectangular microstrip patch antenna are designed at resonant frequency of 2 GHz for single-mode. The advantages of this method are to realize the integration that can be transformed for broadband applications as well as can be applied to the any integration systems between microwave filter and antenna. TE_{10} is used as a dominant mode to realize a single-mode of the microwave filter and antenna as a mode of propagation. It is because TE_{10} mode is a dominant mode that able to operate over a broad spurious free bandwidth which existing inside the rectangular waveguide with the lowest cut-off frequency. This paper will focus on a multilayer approach for integrating microwave filter and antenna.

II. RESONANT CIRCUIT OF SIW FILTER AND ANTENNA

In this section, a low-pass prototype equivalent circuit is used to produce single-mode SIW filter and microstrip patch antenna equivalent circuit as shown in Fig. 3. The impedance inverter, K_{01} and $K_{N,N+1}$ represent the coupling method between the input port and the output of the filter. In Fig. 4 shows the equivalent circuit of single-mode based on the low-pass prototype circuit [15]. One of the most important on designing the equivalent circuit of rectangular SIW filter and rectangular microstrip patch antenna is used to integrate with any relevant equivalent circuit of filter with any suitable common impedance matching of 50 Ω between two elements.

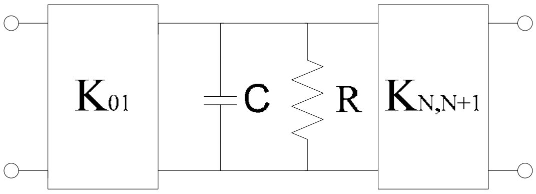
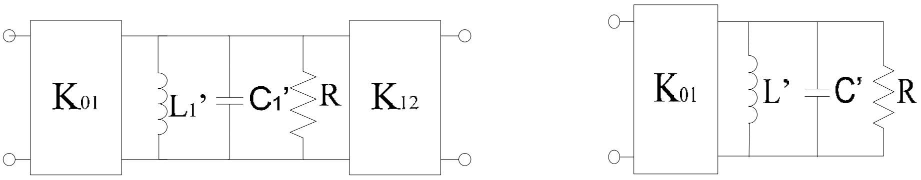


Fig.3. Low-pass equivalent circuit



(a) (b)

Fig.4. Single-mode circuit of (a) rectangular SIW filter and (b) rectangular microstrip patch antenna

The capacitance C_r and the impedance inverter $K_{r,\,r+1}$ value of the low-pass prototype can be determined using the following equations [1][16]:

$$C_r = \frac{2}{\eta}\sin\left[\frac{(2r-1)\pi}{2N}\right] \tag{1}$$

$$K_{r,r+1} = \frac{\left[\eta^2+sin^2(r\pi/N)\right]^{1/2}}{\eta} \tag{2}$$

where the number of orders, N of the network and η is defined as [1][16]:

$$\eta = sinh\left[\frac{1}{N}sinh^{-1}\left(\frac{1}{\epsilon}\right)\right] \tag{3}$$

while ϵ is the ripple of insertion loss. The transformation of the low-pass prototype equivalent circuit into bandpass equivalent circuit can be determined using the following equations [1][16]:

$$L'_r = \frac{1}{\alpha C_r \omega_o} \tag{4}$$

$$C'_r = \frac{\alpha C_r}{\omega_0} \tag{5}$$

where ω_o is the geometric midband frequency; C'_r is capacitance; L'_r is inductive; α is the bandwidth scaling factor and the r is representative as number of orders. The resistances, R acts as load of the prototype circuit.

III. SINGLE-MODE SIW CAVITY

Waveguide is frequently used in wireless communication systems which has the benefit in term of a high power handling capabilities, operate at higher frequency and low loss [17] but it has disadvantages in terms of bulky in size and high manufacturing cost [18]-[20]. The SIW filter is an artificial waveguide which is constructed on a planar structure with arrays of metalized via holes inside the cavity [21]. Therefore, SIW filter is applied based on the rectangular waveguide concept so that it can be integrated with any planar structure.

The design rules for the rectangular SIW based upon TE_{mnt} are determined by the resonant frequency [22]-[25]:

$$f_{r(mnt)} = \frac{v_c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{m\pi}{a_{eff}}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{t\pi}{l_{eff}}\right)^2} \tag{6}$$

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

$$a_{eff'} = a_{SIW} - \frac{d^2}{0.95p} \quad , \quad l_{eff'} = l_{SIW} - \frac{d^2}{0.95p} \tag{7}$$

where, l_{SIW} and w_{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 metalized via holes diameter, d and pitch, p can be calculated using the design rules from the following equations [23]-[26] as shown in Fig. 5.

$$d > 0.2\lambda_o \quad , \quad \frac{d}{p} \leq 0.5 \tag{8}$$

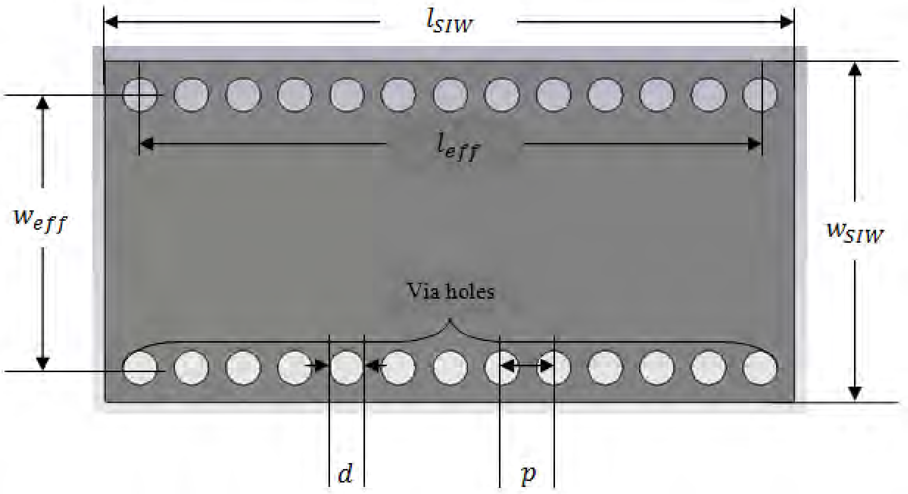


Fig.5. Top view of SIW filter

IV. MICROSTRIP PATCH ANTENNA

The rectangular microstrip patch antenna is used to integrate with a rectangular SIW filter because it has attractive features such as light weight, conformability and low cost [27]-[28]. The structure of the rectangular microstrip patch antenna is shown in Fig. 6.

The physical dimension of the rectangular microstrip patch antenna can be determined by the width, w_a and the length, L_a as following equation [28]-[30]:

$$w_a = \frac{c}{2f_c}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{9}$$

$$L_a = \frac{1}{2f_c\sqrt{\varepsilon_{eff}}\sqrt{\mu_r\varepsilon_r}} \tag{10}$$

where f_c is the centre frequency and ε_{eff} is the efficient permeability. ΔL extended incremental length of the patch can be calculated using the equation [29],[30]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)} \tag{11}$$

h is the thickness of the dielectric substrate. The resistance at the edge of the patch can be used to design a matching network for the patch antenna. The total of the feed line can be determined by using equation [29]:

$$y_{total} = y_o + y_1 \tag{12}$$

where

$$y_1 = \left(\frac{L_a}{2} - y_o\right) + \frac{\lambda_g}{4} \tag{13}$$

where λ_g is the centre guide wavelength and y_o is the inset feed line for microstrip patch antenna.

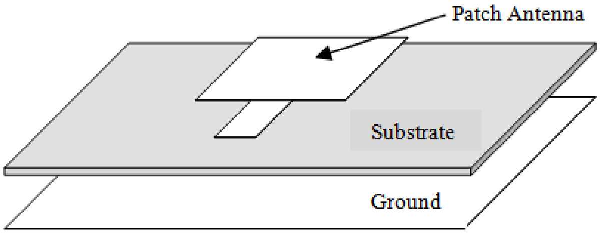


Fig.6. Microstrip patch antenna structure

V. INTEGRATED SIW FILTER AND MICROSTRIP PATCH ANTENNA USING MULTILAYER STRUCTURE

The integrated of the equivalent circuit for the rectangular SIW filter and rectangular microstrip patch antenna can be developed in a multilayer structure as shown in Fig. 7 as well as the physical layout shown in Fig. 8. T-slot is introduced into this structure as a coupling aperture to couple between SIW filter and antenna. The combination between SIW filter and antenna has the advantage where the structure can be directly coupled without external impedance matching circuit. Fig. 9 shows the measurement setup for Device Under Test (DUT) using Vector Network Analyzer (VNA).

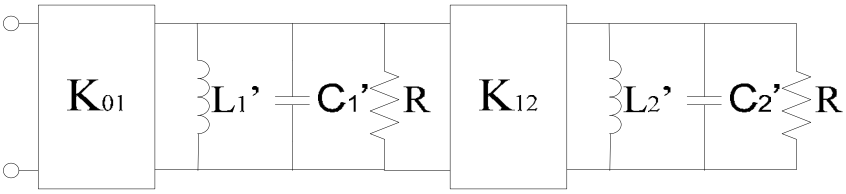


Fig.7. Integrated equivalent circuit for multilayer between the rectangular SIW filter and rectangular microstrip patch antenna for single-mode

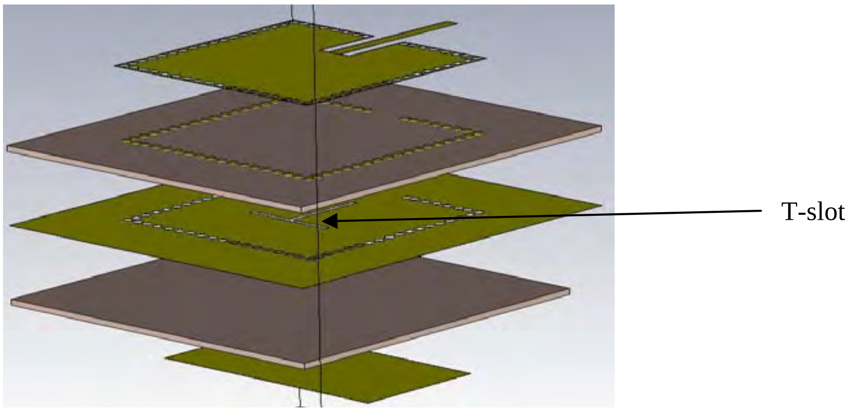


Fig.8. Multilayer approach between rectangular SIW filter and rectangular microstrip patch antenna

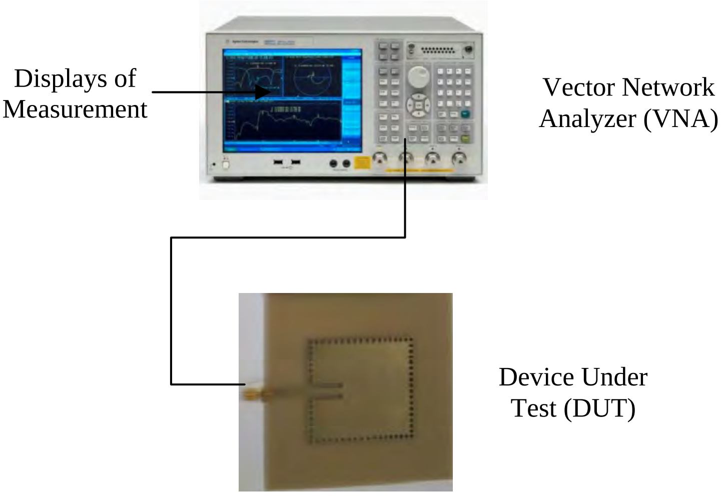
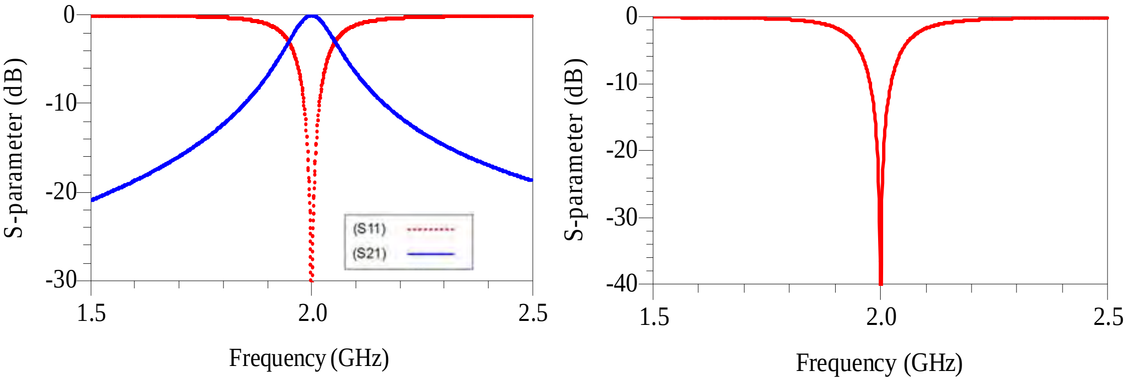


Fig.9. Measurement setup on DUT using VNA

VI. Results and Discussion

The single-mode rectangular SIW filter and rectangular microstrip patch antenna equivalent circuit has been designed at centre frequency 2 GHz to obtain the coupling value, $K_{01} = K_{12} = 50$, capacitance, $C' = 60.6324$ pF and inductance, $L' = 104.4382$ pH for rectangular SIW filter meanwhile for rectangular microstrip patch antenna the coupling value, $K_{01} = 50$, capacitance, $C' = 60.6324$ pF and inductance, $L' = 104.4382$ pH by using equation (1) - (5).

The simulated results of the rectangular SIW filter and rectangular microstrip patch antenna equivalent circuit is shown in Fig. 10. The return loss, S_{11}, with better than -20 dB, insertion loss, S_{21} of 0 dB with a bandwidth of around 35 MHz have been achieved for rectangular SIW filter simulation results and meanwhile for rectangular microstrip patch antenna, the return loss, S_{11}, with better than -30 dB with a bandwidth of around 35 MHz have been achieved.

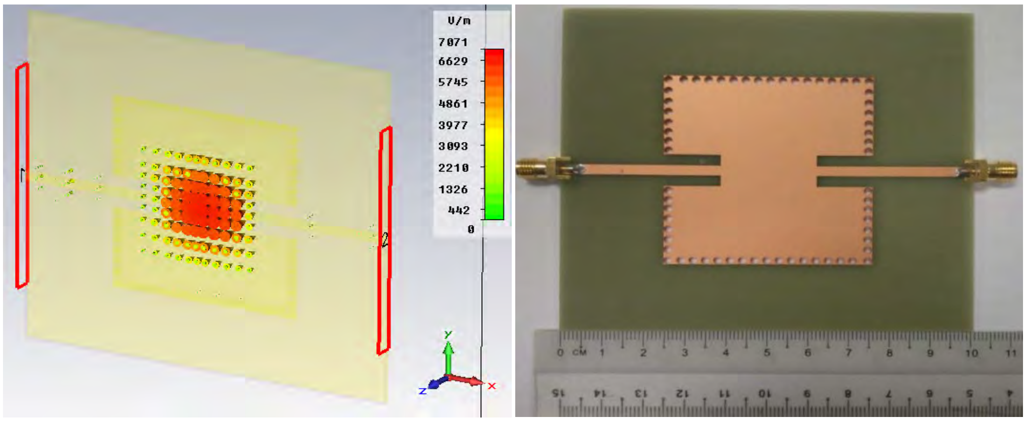


(a) (b)

Fig.10. Simulation results of equivalent circuit (a) rectangular SIW filter (b) rectangular microstrip antenna for single-mode

The physical layout design of the rectangular SIW filter and rectangular microstrip patch antenna is then simulated using CST Microwave Studio software. The devices are constructed using FR-4 material on a 1.6 mm dielectric substrate thick with dielectric constant ε_r = 4.6. The copper thickness is 0.035 mm and the loss tangent is 0.019. The dimensions of rectangular SIW can be calculated using equations (6) – (8). Similarly for the rectangular microstrip patch antenna, the dimensions can be determined using equations (9) – (13).

The Electric field (E-field) for the TE$_{10}$ mode of the rectangular SIW filter at centre frequency of 2 GHz is shown in Fig. 11(a). The simulations show the magnitude of E-field is typically concentrated in the centre of SIW cavity. The array of via-holes of the SIW cavity is used as a boundary to prevent the Electromagnetic (EM) fields leak from device. The physical layout of the rectangular SIW resonator filter from the manufacturing fabrication is shown in Fig. 11(b).



(a) (b)

Fig.11. E-field distribution of rectangular SIW filter in single mode at centre frequency of 2 GHz (b) Manufacturing single-mode rectangular SIW bandpass filter

Fig. 12 shows the simulated and measured results on the rectangular SIW filter. The physical length, l_{SIW} and width, a_{SIW} of SIW filter are 100.6 mm and 92.6 mm, whilst the via-hole diameter, d = 2 mm and the pitch, p = 3 mm respectively. The return loss (S_{11}) and an insertion loss (S_{21}) of -16.67 dB and -1.5 dB with a bandwidth of around 108 MHz are obtained. In the measurement results, the centre frequency of 2.045 GHz with a return loss (S_{11}) and insertion loss (S_{21}) of -21.03 dB and -1.57 dB and bandwidth of around 236.7 MHz are measured. However, there is nevertheless a noted frequency shift of 45 MHz (2.25%) from the centre frequency, which is due to the variations of permittivity in the substrate, i.e. 4.6 ± 0.15 (≈ up to 3.26%) and the inconsistencies of dielectric thickness, i.e. 1.6mm ± 0.025 (≈ up to 1.56%) , as well as manufacturing tolerance. The losses which occurred, particularly in the passband are due to the losses at the transitions from microstrip to SIW and also through SMA connectors. In addition, radiation loss through the surface of the SIW cavity, and leakage through via-holes and pitches, also contributes a small amount of loss.

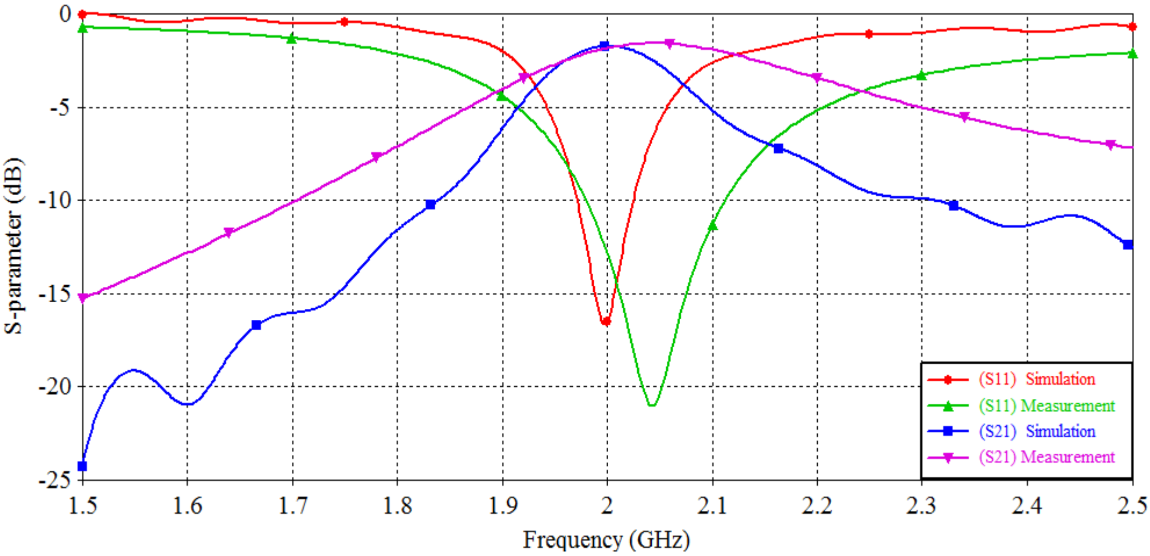
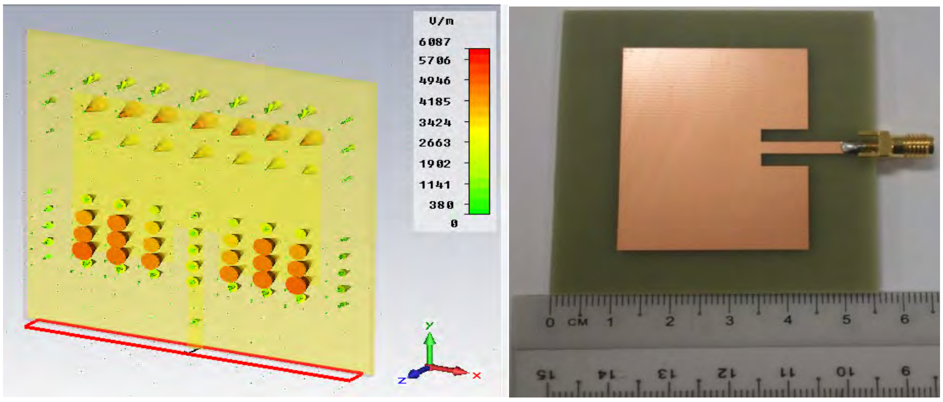


Fig.12. Comparison of simulated and measured response

The E-field for TE_{10} mode on the rectangular microstrip patch antenna at centre frequency of 2 GHz is shown in Fig. 13(a). There is a noted less concentration of the E-field in the rectangular patch antenna cavity due to the antenna is a radiating element which is used to transmit or recieve signals from other antenna. Fig. 13(b) shows the physical layout of microstrip patch antenna.



(a) (b)

Fig.13. E-field distribution for rectangular microstrip patch antenna in single mode (TE_{10}) at centre frequency of 2 GHz (b) Manufacturing single-mode rectangular microstrip patch antenna

Fig. 14 shows the simulated and measured results on the rectangular microstrip patch antenna. The simulated return loss (S_{11}) is -37.58 dB with a bandwidth of around 41.98 MHz are obtained. In the measurement results, the centre frequency of 2.05 GHz with a return loss (S_{11}) of -26.94 dB and bandwidth of around 48.54 MHz are achieved. However, there is nevertheless a noted frequency shift of 50 MHz (2.5%) from the centre frequency, which is due to the variations of permittivity in the substrate, i.e. 4.6 ± 0.15 (≈ up to 3.26%) and the inconsistencies of dielectric thickness, i.e. 1.6mm ± 0.025 (≈ up to 1.56%), and also manufacturing tolerance.

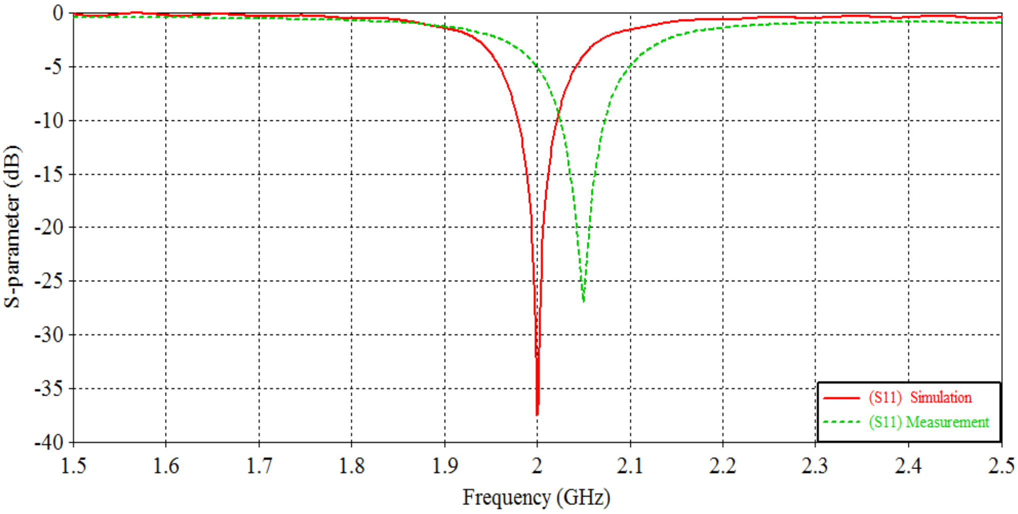


Fig.14. Comparison of simulated and measured response

The simulated far-field radiation pattern indicates that the forward directional pattern of the rectangular microstrip patch antenna. The main and side lobes can be observed in simulated two dimensional radiation pattern as shown in Fig. 15. The simulated pattern represents the main lobe magnitude of 5.1 dB at 1.0 degree direction from the origin point at centre frequency 2 GHz and meanwhile for measurement gives the magnitude of 5.1 dB at 0.0 degree direction from the origin point However, there is a slight difference in the pattern due to environmental factors like wireless signal interference.

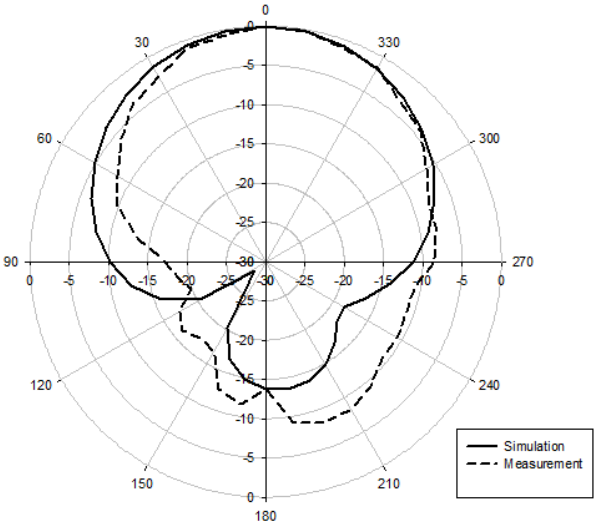


Fig.15. Comparison of simulated and measurement of radiation pattern

The investigation is then carried out on the multilayer designed in between microwave filter and the patch antenna. The design value for coupling value, K_{01} = 50 and K_{12} = 59.845, capacitance, C_1' = C_2' = 59.2173 pF and inductance, L_1' = L_2' = 106.9340 pH based on Fig. 7. Fig. 16 shows the simulated results of equivalent circuit for multilayer structure. It shows that the return loss, S_{11}, with better than -15 dB with a bandwidth of around 50 MHz have been obtained.

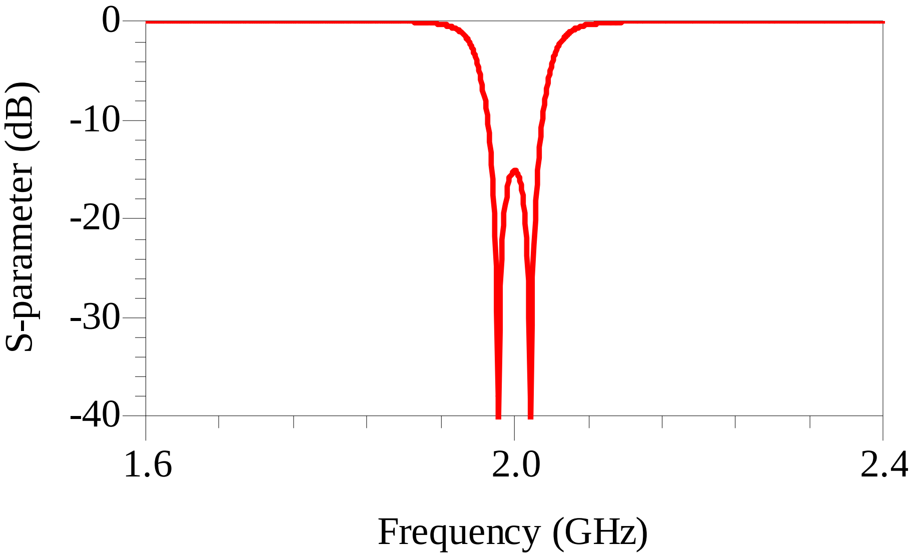


Fig.16. Simulated response of single-mode integrated filter and antenna

The design is then carried out on the simulation multilayer structure for microwave filter and antenna with T-slot as shown in Fig. 17. From the simulation, it is found that the position of the T-slot, h_4 at ground plane is considered and needs to be optimized in order to achieve a better response shown in Fig. 18. Fig. 19 shows the variation of the position, h_4, of the integrated SIW filter and patch antenna resonator, indicating that the increase or decrease will affect the value of return loss (S11). In this analysis, at centre frequency of 2.003 GHz, with return loss of -8.43 dB, the value of h_4 is 41 mm (1st), at centre frequency of 1.998 GHz with return loss of -21.93 dB, the value of h_4 is 39 mm (2nd) and at centre frequency of 1.996 GHz with return loss of -5.83 dB, the value of h_4 is 37 mm (3rd). As the value of h_4 increases or decreases, there is a minor change in the centre frequency as well as in the value of return loss (S11).

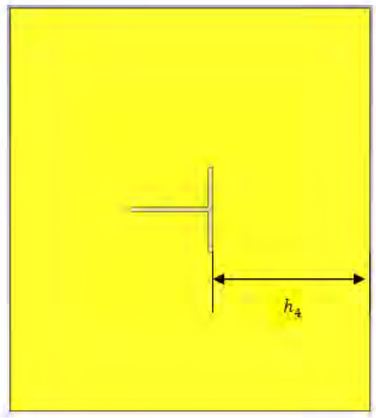


Fig.17. Ground plane view with T-slot

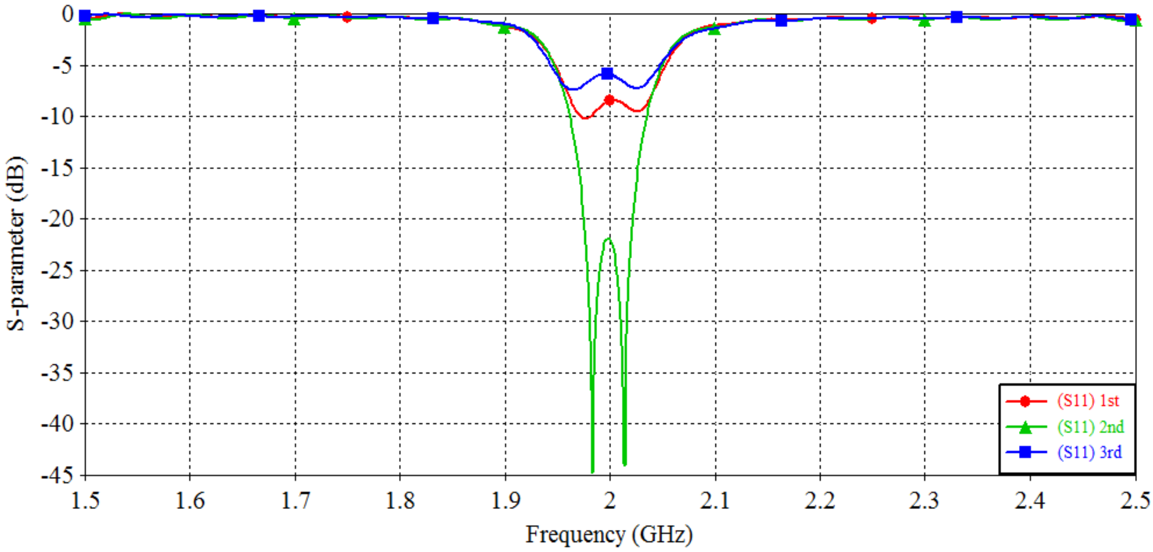


Fig.18. Effect h_4 of the multilayer structure

The simulated and measured far-field radiation pattern as shown in Fig. 20 indicates the forward directional pattern of the multilayer structure. The simulated pattern represents the main lobe magnitude of 5.26 dB at 180 degree direction from the origin point at centre frequency of 2 GHz and meanwhile for measurement gives the magnitude of 5.2 dB at 180.0 degree direction from the origin point However, there is a slight difference in the pattern due to environmental factors like wireless signal interference.

The electromagnetic field's pattern for the multilayer rectangular SIW filter and microstrip patch antenna at 2 GHz are shown in Fig. 21. The simulation results show the magnitude of E-field is concentrated in the centre of the SIW cavity while for the antenna cavity is less concentration due to the fact that the antenna is a radiating element. Fig. 22 shows the simulated and measured results on the multilayer structure. The simulated return loss of -21.93 dB and bandwidth of 73.1 MHz is achieved especially in the passband. For the measurement results, the centre frequency of 2.075 GHz with a return loss (S_{11}) of -11.16 dB and bandwidth of around 103.58 MHz are achieved. Fig. 23 shows the manufactured integrated SIW filter and patch antenna with the final length and width dimension of 89 mm and 100 mm (top); 79 mm and 100 mm (bottom) and with a total thickness of 3.34 mm. Table 1 shows the overall summary for the single-mode design of SIW filter, microstrip antenna and integrated SIW filter and antenna.

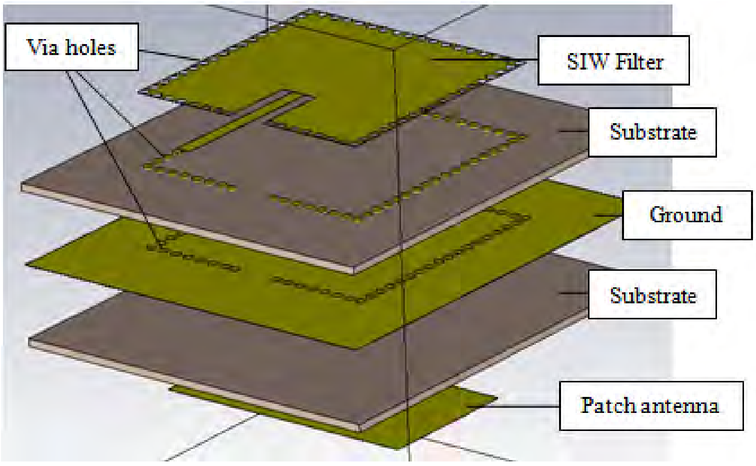


Fig.19. Multilayer structure between SIW filter and microstrip patch antenna

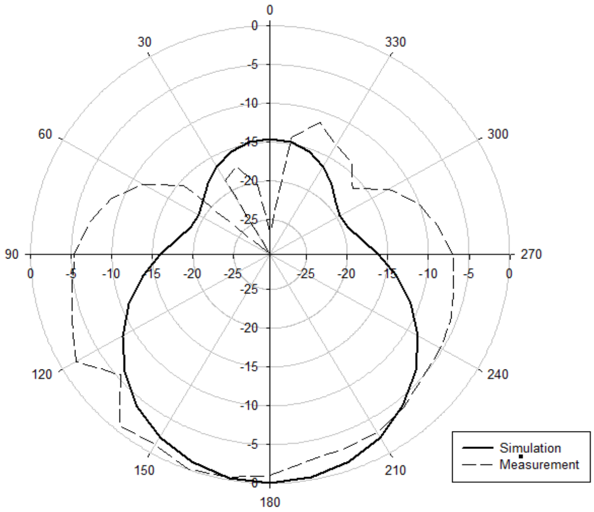
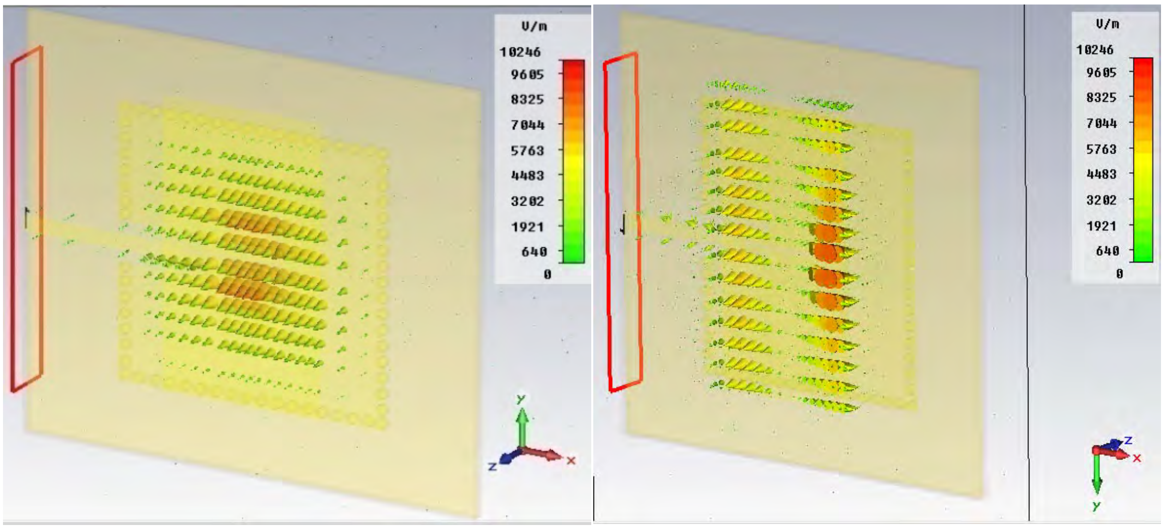


Fig.20. Comparison of simulated and measurement for radiation pattern



(a) (b)

Fig.21. E-field distribution of multilayer structure (a) top view (b) bottom view

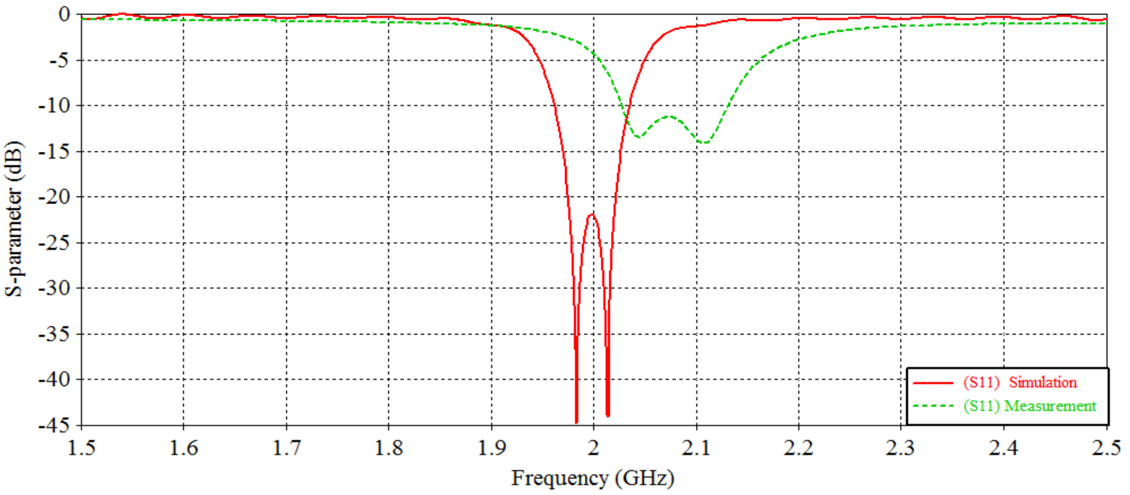
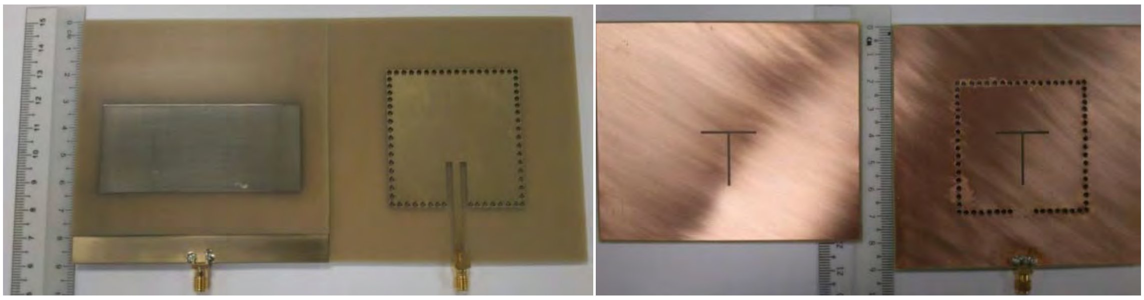


Fig.22. Comparison of simulated and measured response



(a) (b)

Fig.23. (a) Manufacturing integrated single-mode SIW filter and patch antenna (from left: bottom and top) (b) T-slot at ground plane

TABLE I

Summary comparison simulated with measurement results

		Frequency (ies) (GHz)	Return Loss S_{11} (dB)	Insertion Loss S_{21} (dB)	Bandwidth (MHz)	Main Lobe magnitude (dB)
SIW Filter	Simulation	2.000	-16.67	-1.50	108.0	-
	Measurement	2.045	-21.03	-1.57	236.7	-
Microstrip patch antenna	Simulation	2.000	-37.58	-	41.98	5.1
	Measurement	2.050	-26.94	-	48.54	5.1
Multilayer	Simulation	2.000	-21.93	-	73.1	5.26
	Measurement	2.075	-11.16	-	103.58	5.2

VII. CONCLUSION

In this paper, the realization of integrated rectangular SIW filters and rectangular microstrip patch antenna has been successfully presented. A technique to produce single-mode multilayer rectangular SIW filter and microstrip patch with T-slot coupling has been developed. The simulated results show a good agreement with the ideal circuit as well as the measurement results. This new class of integrated filter and antenna to produce filtering and radiating element in a single module would be useful in microwave RF front-end subsystems where the reduction of overall physical volume, performance and cost is very important.

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