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The Integration Of Rectangular SIW Filter and Microstrip Patch Antenna Based On Cascaded Approach

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Abstract

This paper presents the technique for integrating the rectangular Substrate Integrated Waveguide (SIW) filter with the rectangular microstrip patch antenna to produce filtering and radiating element in a single device. To proof the concept, the integrated microwave filter and antenna at center frequency of 2 GHz was demonstrated and validated through simulation and measurement. It demonstrated promising measured results, which were ingood agreement with the simulated results. The integrated microwave filter and antenna would be beneficial in microwave systems where the reduction of overall volume and weight as well as cost is very important such as in base stations and multiplexer in any communication systems.

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Keywords: Microwave Filters; Antenna; Bandpass Filters; Substrate Integrated Waveguide.

1. Introduction

In general, microwave filter and antenna in any communication systems are designed separately and then connected using50Ω common reference impedance. However, there is a growing interest in the integration of microwave filter and antenna in order to reduce the overall physical volume and cost in the RF front-end subsystems. Some techniques have been proposed in [1][2][3][4] to realize the integration between filter and antenna. However, the technique applied to the integration of the filter and antenna in [1], [2] using meandered slots are difficult to design due to its meandered slots structure. In [3] and [4], the filter and antenna were designed with extra impedance structure and applied on the both elements. However, the structure increased complexity of the overall physical volume, weight and losses.

In this paper, a new class of integrated filter and microstrip based on rectangular SIW resonator and microstrip is presented. The integrated filter and antenna is designed at center frequency of 2 GHz. TE_{10} mode of propagation is used as a dominant mode to realize single-mode of the microwave filter and antenna. It is because $TE_{10}$is a dominant mode existing inside the rectangular waveguide which can operate over a broad spurious free bandwidth with the lowest cut-off frequency [5].

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2. Theory and Design Analysis

2.1. Single mode SIW Cavity

Rectangular waveguide is commonly used in wireless communication systems which have the benefit from its high power handling capabilities and low loss [6], but it is nevertheless relatively bulky and expensive [7]. Therefore, Substrate Integrated Waveguide (SIW) filter is applied on the rectangular waveguide so that it can be easily integrated with any planar elements [8].

SIW is an artificial waveguide which is constructed on a planar substrate with periodic arrays of metalized via holes as shown in Fig. 1.

The ruleto design the rectangular SIW filter isbased upon TE_{10} mode that can be determined by the resonant frequency from [8], [9]:

$$f_{r(10)} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{\pi}{a_{eff}}\right)^2 + \left(\frac{\pi}{l_{eff}}\right)^2} \quad (1)$$

For the TE_{10} mode, the efficient width, a_{eff}, and length, l_{eff}, of the resonant SIW cavity are given by[8], [10]:

$$a_{eff} = a_{SIW} - \frac{d^2}{0.95p}, \; l_{eff} = l_{SIW} - \frac{d^2}{0.95p} \quad (2)$$

where a_{SIW} and $l_{SIW}$are the width and length of the resonant SIW cavity, *d* and *p* are the diameter and the distance between adjacent vias respectively. c is the speed of light in free space,μ_r is the relative permeability, whilstε_r is the dielectric permeability of the substrate respectively. The metalized via holes diameter, *d,* and pitch, *p*, can be calculated using the design rule from the following equation [11]:

$$d > 0.2\lambda_o \quad , \quad \frac{d}{p} \leq 0.5 \quad (3)$$

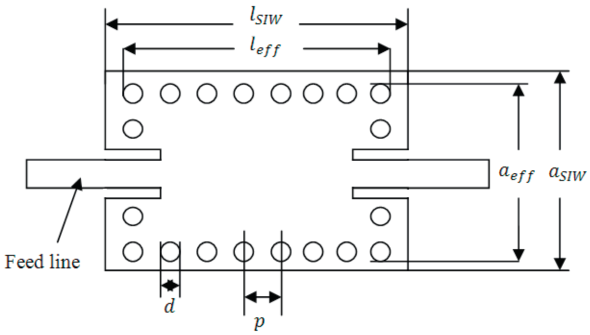

Fig 1. Effective dimension of rectangular SIW cavity with via holes

2.2.Microstrip patch antenna

The rectangular microstrip patch antenna will be used in the integration with the rectangular SIW filter. The structure of the microstrip patch antenna is shown in Fig. 2 where the patch layer and ground layer is etched on the substrate layer [12].

The physical dimension of the rectangular microstrip patch antenna can be determined by the width $w_a$and the length, L_aErr[13]:

$$w_a = \frac{c}{2f_c}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (4)$$

$$L_a = \frac{1}{2f_c\sqrt{\varepsilon_{eff}}\sqrt{\mu_r\varepsilon_r}} \tag{5}$$

where f_c is the center frequency and ε_{eff} is the efficient permeability. *ΔL,* extended incremental length of the patch can be calculated using the equation below [13]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{6}$$

h is the thickness of the dielectric substrate and y_o can be calculated using[13]:

$$y_o = \frac{L_a}{\pi}cos^{-1}\left[\frac{150}{R}\right]^{1/2} \tag{7}$$

where R is the impedance of the feed line and y_o is the inset feed as shown in Fig. 2.

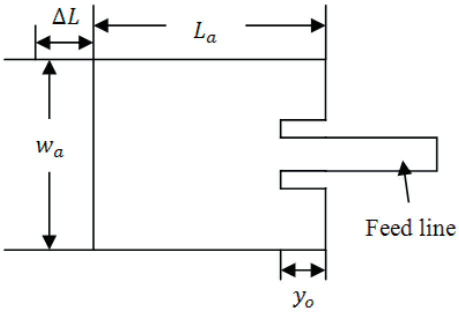

Fig. 2. Dimension of rectangular microstrip patch antenna

2.3.Integration of SIW Filter and Microstrip Patch Antenna

The integration of the rectangular SIW filter and rectangular microstrip patch antenna can be designed in a cascade structure. The structure provides the maximum cut-off frequency and gives better return loss of the filter as well as reducing the overall physical volume. A 50 Ω transmission line is used to integrate between filter and antenna. Fig. 3 shows the structure of cascaded form between the rectangular SIW filter and rectangular microstrip patch antenna.

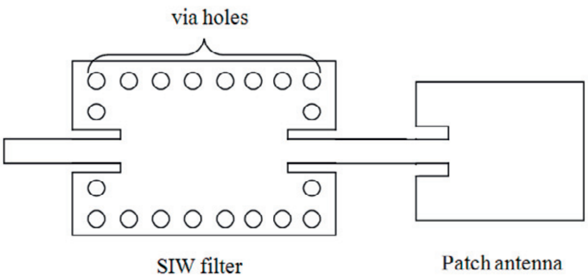

Fig. 3. Cascade structure between rectangular SIW Filter and rectangular microstrip patch antenna

3. Simulation and Experimental Results

To validate the concept, the design of the filter and antenna are simulated using CST Microwave Studio. The devices are constructed using FR-4 on a 1.6 mm dielectric substrate thick with dielectric constant ε_r= 4.6. The thickness of copper 0.035 mm and the loss tangent is 0.019. The dimension of the rectangular SIW can be determined using equations (1) – (3).

Similarly for the rectangular microstrip patch antenna, the dimensions can be determined using equations (4) – (7).

The electric field for the TE_{10} mode on SIW filter at 2 GHz is shown in Fig.4. 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.

Fig. 5 shows the simulated and measured results for the rectangular SIW filter. The physical length, l_{SIW} and width, a_{SIW} of SIW filter are 48.75 mm and 51.62 mm, whilst the via-hole diameter, d = 1 mm and the pitch, p = 3 mm respectively. The return loss (S_{11}) and insertion loss (S_{21}) of -6.41 dB and -0.5 dB with bandwidth of around 380 MHz are obtained. In the experimental results, the center frequency of 2.045 GHz with return loss (S_{11}) and insertion loss (S_{21}) of -21.03 dB and -1.57 dB and bandwidth of around 348 MHz are measured. However, there is nevertheless a noted frequency shift of 45 MHz form the center frequency, which is due to the variations of dielectric permeability and manufacturing tolerance.

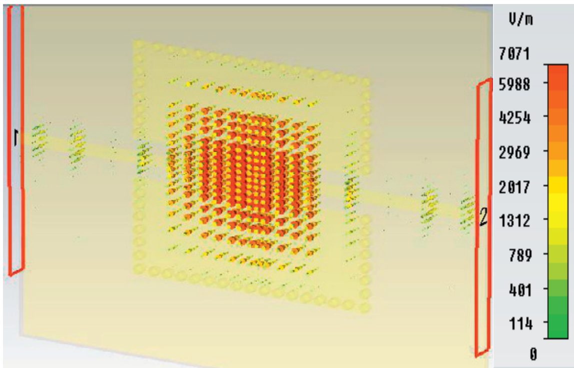

Fig. 4. E-field distribution for rectangular SIW filter in single mode (TE_{10}) at 2GHz

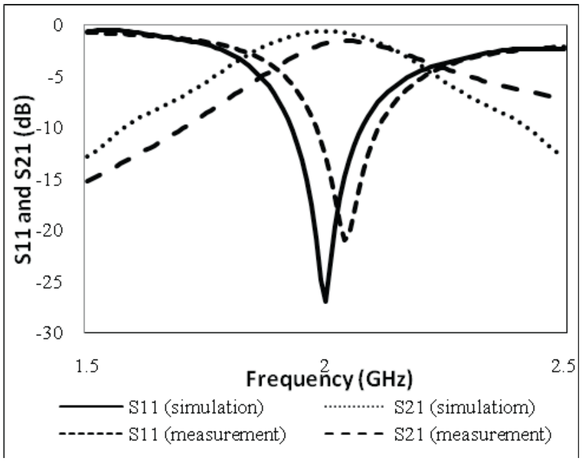

Fig. 5. Simulated and measured results on rectangular SIW filter designed at 2GHz

The elecrtric field for the TE_{10} mode on rectangular microstrip patch antenna at 2 GHz are shown in Fig. 6. There is a noted less concentration of the E-field in the antenna cavity due to the fact that the antenna is a radiating device.

Fig. 7 shows the simulated and measured results for the rectangular microstrip patch antenna. The simulated return loss (S_{11}) is -26.81 dB with bandwidth of around 41.99 MHz are obtained. As for the experimental results, the center frequency of 2.05 GHz with return loss (S_{11}) of -26.94 dB and bandwidth of around 48.56 MHz are achieved. There is a noted frequency shift of about 50 MHz from the center frequency, which is due to the variations of dielectric permeability and manufacturing tolerance.

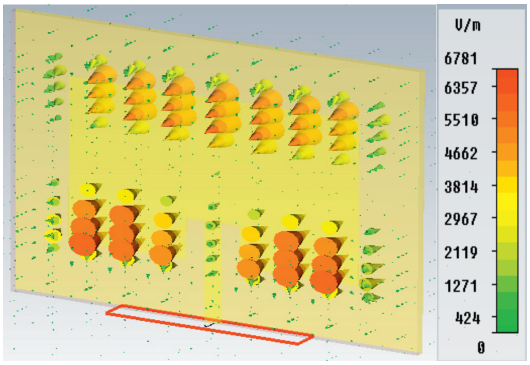

Fig. 6. E-field distribution for rectangular microstrip patch antenna in single mode (TE_{10}) at 2GHz

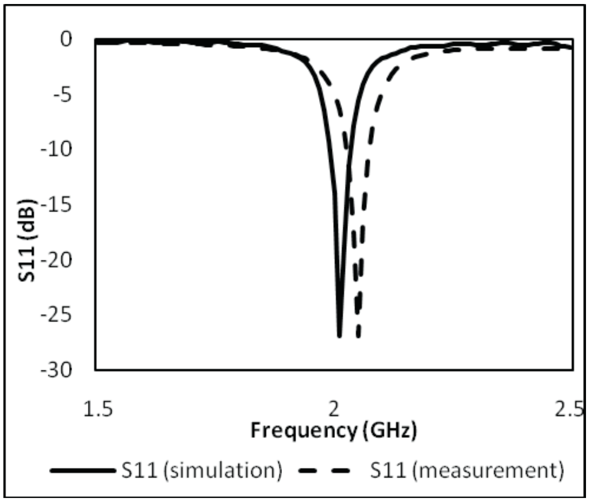

Fig. 7. Simulated and measured results on rectangular microstrip patch antenna designed at 2GHz

The analysis is then carried out on the cascaded integration between microwave filter and antenna. Fig. 8 shows the radiation pattern for the single-mode antenna at 2 GHz. The pattern represents the main lobe magnitude of 4.9 dB at 2.0 degree direction from the origin point.The electric field for the integrated rectangular SIW filter and microstrip patch antenna at around 2 GHz are shown in Fig. 9.The simulated response for the integrated filter and antenna is shown in Fig. 10. The return loss (S_{11}) of -12 dB and bandwidth of 78.01 MHz are achieved especially in the passband. In the experimental results, the center frequency of 2.13 GHz with return loss (S_{11}) of -4.55 dB is achieved. However, there is also a frequency shift of 130 MHz from the desired center frequency, which is due to the variations of permittivity in the substrate, i.e. 4.6 ± 0.15 and the inconsistencies of dielectric thickness, i.e. $1.6\text{mm} \pm 0.025$, and also manufacturing tolerance. The small amounts of losses in the measured response are due to the losses of transition from microstrip to SIW, copper loss through conductivity, radiation loss through the surface of the SIW cavity, and losses through SMA connectors. The manufactured integrated microwave filter and antenna, with overall length and width dimension of 165.56 mm x 72.62 mm, is shown in Fig. 11. The overall physical volume can be further reduced by developing the prototype of integrated rectangular SIW filter and antenna based upon multilayer approach.

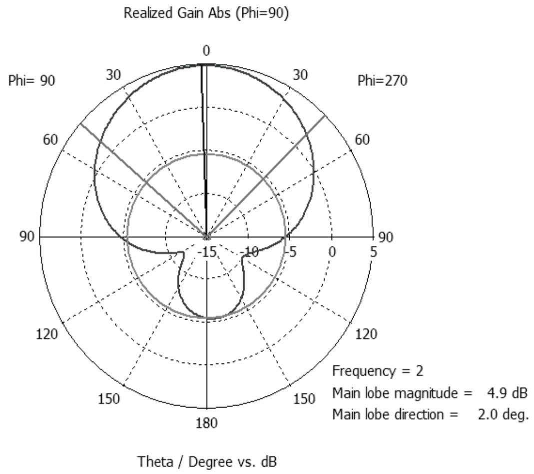

Fig. 8. Simulated radiation pattern for single-mode at frequency 2 GHz

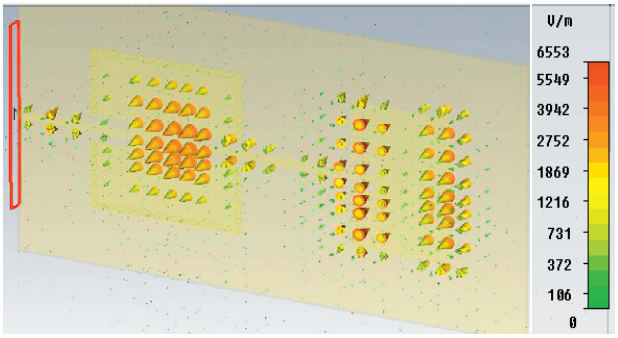

Fig. 9. E-field distribution for integrated rectangular SIW filter and rectangular microstrip patch antenna in single mode (TE_{10}) at 2GHz

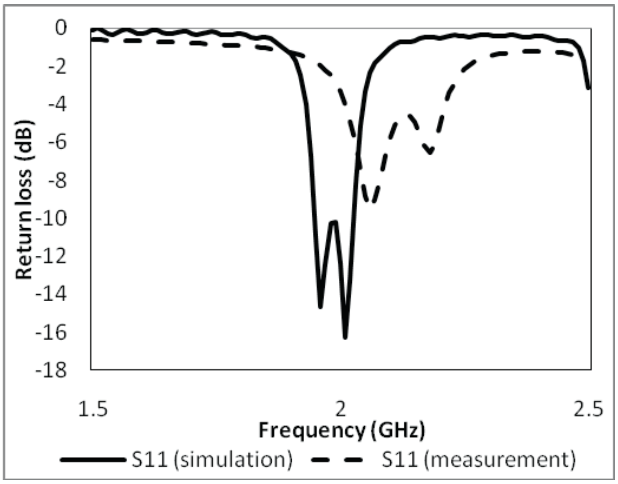

Fig. 10. Simulated and measured results on integrated rectangular SIW filter and rectangular microstrip patch antenna designed at 2 GHz

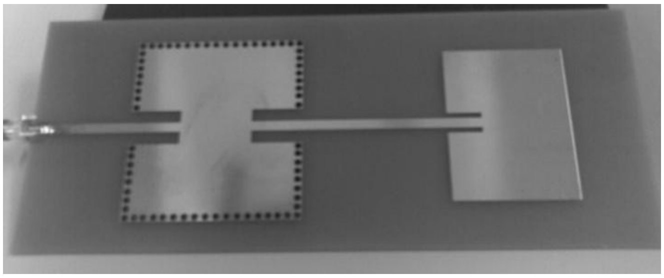

Fig. 11. Fabricated design for cascaded structure between rectangular SIW filter and rectangular microstrip patch antenna

4. Conclusion

A new design of integrated rectangular SIW filter with rectangular microstrip patch antenna has been successfully designed, manufactured and measured. The experimental results show good agreement and in-line with the simulated performance. 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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