Novel Design of Multilayer WLAN Filter having Compact Size with Improved Performance

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Abstract

Due to the development of wireless communications and the appearance of new systems there is high demand in small size, low cost filters with high performance. Hence, miniaturization of band pass filters with improvement of their characteristics is a big challenge in modern filters design. This is achieved by improvement of conventional concepts and approaches, as well as by introduction of new topologies and designs. Multi-layer concept in conventional filter designing prove to be the best approach to meet the challenges in modern filter design.

In this research work, a new method to design a Multi-layer band pass filter (BPF) is presented for WLAN applications. This method is based on a simple principle: different substrates (dielectric constants) will result different resonant frequencies for a resonator. The basic structure of this method is studied and then a planar band pass filter is designed to utilize in this structure. To reduce the filter size, dual layer filter is proposed but increase in insertion loss due to multi-layer coupling.

To overcome this issue, the Substrate Integrated Waveguide (SIW) filter is established based on multilayer technique. To prove the concept of microwave WLAN filter, the operating central frequency of 2.44 GHz is demonstrated and validated through simulation and measurement. Finally, the multilayer configuration with dielectric substrates showed that the bandwidth is broaden up, insertion loss, return loss and size are reduced than single layer configuration.

Keywords: WLAN filter, Planar band pass filter, Insertion loss, return loss, Substrate Integrated Waveguide, Single layer, Multilayer Technique.

Introduction

Wireless Local Area Networks encompass one of the wildest emergent segments of the Telecommunications Industry. The implementation of WLAN solutions in many market segments including but limited to small office / home office (SOHO), manufacturing and industrial plants, small and large businesses, public hotspots, convention centers, hotels, airports and even Government Sectors, has ignited with the completion of industry standards and the corresponding release of WLAN products by leading manufacturers [3]. WLAN technology is not only the option for providing high-speed Internet access to the public in large but also used to save costs and avoid laying cable networks. Whatever the cause, WLAN solutions are popping up everywhere.

Nowadays, telecommunication industry has developed such new Wireless techniques such as Wireless LAN and Bluetooth technology especially for WLAN applications and Filters are vital part to the operations of this technology. With the advancement and development of wireless communication of WLAN, narrow band RF / microwave bandpass filters with low insertion loss, high selectivity and most importantly the reduced size has gained extraordinary demand.

WLAN application utilizes the frequency spectrum in the Industrial Scientific and Medical (ISM) bands established in 1947 out of the radio spectrum by the International Telecommunication Union (ITU) to provide dedicated spectrum for non-telecommunication devices. Initially, the ISM bands are limited to Industrial Scientific and Medical devices, and usage of telecommunication was not allowed [3]. However, several factors conveyed about the gravity to use the unlicensed ISM bands for wireless communication with the rapid evolution of microelectronics and computing along with the attractiveness of an unlicensed spectrum over the period of time.

A part of the radio frequency spectrum/ electromagnetic spectrum from 9 KHz to 275 GHz is covered and regulated by the ITU (International Telecommunication Union) Radio Regulations. The applications [4] of microstrip filters can be realized in wide areas wireless applications such as:

- Cordless telephones (2.4 GHz or 5.8 GHz)
- Cellphones [Cellphones use 1.9 GHz frequency unlike cordless telephones]
- Router (2.4 or 5 GHz)
- Bluetooth (2.4-2.485 GHz) earpiece
- Baby monitor (49 MHz, 902 MHz or 2.4 GHz) etc.

Wireless LAN (WLAN) network generally using the 2.4 GHz (12 cm) UHF and 5 GHz (6 cm) SHF ISM radio frequency bands to connect electronic devices through Wi-Fi technology. High performance and small-size microwave filters' demand is evolving fast in various communication systems in the past recent years. In realizing unprecedented demands of WLAN applications, new and exciting challenges are being faced in conventional design theory and circuitry of microwave filters. Technologies in filter designing are still concentrating on how to drive filters in lighter weight, smaller size, lower cost and higher performance requirements.

In order to cope up with these stringent requirements, various kind of planer microstrip filters like resonator filters such as stepped impedance resonator filters and open loop resonator filters have been proposed. However, these type of planar microstrip filters are realized on a single microstrip substrate layer which ultimately leads to large size and costly solution. Therefore, multilayer bandpass filters have recently been gaining attention and importance to overcome the aforementioned problem.

The multilayer structure approach in designing WLAN filters has been proposed for increasing the bandwidth, reducing the size of the microstrip filters making it a cost effective and high performance requirement solution [7].

Problem Statement

New technologies demand compact electronic components and high-performance devices. To work in high efficiency, filters are one of the most important electronic components in such devices. In literature, single layer filter designing by using symmetric couple microstrip is well familiar and documented. However, to achieve more compact size with high performance in this configuration is challenging for the fabrication to be realized. Multilayer filter configuration absolves this kind of challenge by introducing flexible coupling between contiguous resonators on same or different layers consequently miniaturize filter can be realized [1].

Compact structures can be achieved with Hairpin-line in the filter design. It can be obtained by folding the resonators of parallel-coupled half wavelength resonator into a "U" shape. These coupled line resonators that are located at different layers without any ground plane between the adjacent layers can be realized in multilayer configuration but at the cost of more insertion loss due to coupling between the resonators. Therefore, various optimization techniques must carefully be adopted to avoid this kind of issue that can affect the overall response and to achieve the cost effective with high performance solution in multilayer configuration. To overcome this issue, the Substrate Integrated Waveguide (SIW) filter is established based on multilayer technique. This research will contribute towards a reduce size filter with high performance requirements using the latest multilayer stack up model for WLAN application [2].

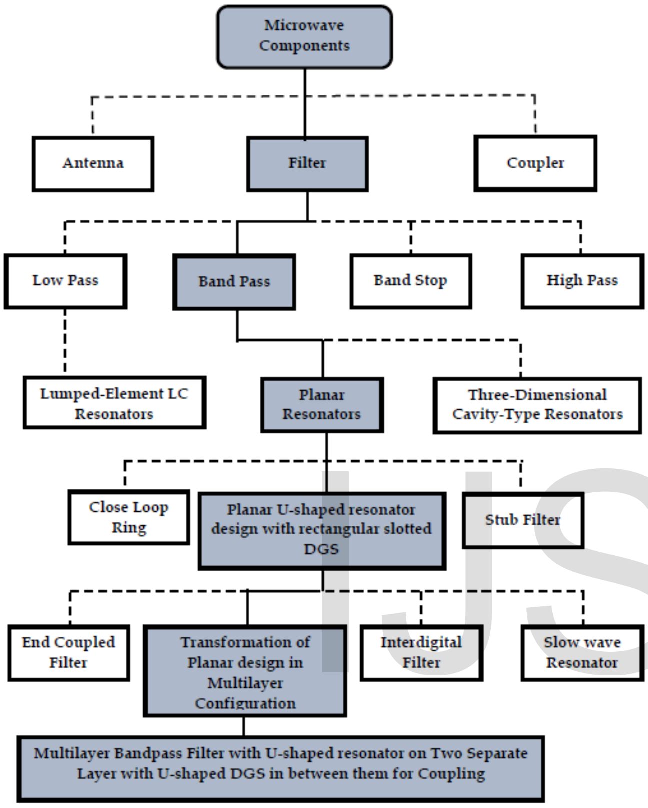
Objective of the Research Work

- The main objective is to understand and design Multi-Layer Filter for WLAN.
- Learn and explore new technology.
- In depth analysis and understanding of Microwave filter theory that will eventually evolve in multilayer filter theory.
- Knowledge of commercial software High Frequency Simulation Software (HFSS) for designing and optimization of microwave filters.
- Finally going through the process of research and writing a research publication will also be one of the main objectives of this thesis.

Scope and Methodology

The overall scope of this research was to achieve improved and compact design with optimum performance requirement of Multilayer Bandpass Filter using planer and SIW resonators at resonator frequency as 2.58 GHz for WLAN applications. First, conventional planar configuration of WLAN bandpass filter having rectangular shaped Defected Ground Structure with cascaded U-shaped resonator is designed to demonstrate the filter size in planar configuration. Then, the cascaded U-shaped resonator is transformed in multilayer configuration having modified U-shaped DGS in between the resonators. The results computation and design optimization in Ansys HFSS simulator revealed that multilayer topology adopted in filter design greatly decrease the overall footprint. Secondly, to further demonstrate the benefits of multilayer topology in microwave filter regime, two layered Substrate Integrated Waveguide (SIW) band pass filter having Surface Plasmonic Polariton (SPP) propagation is proposed. Flow chart in Figure 1.1 and

Figure 1.2 shows the research scope and methodology to achieve the desired objective in the proposed multilayer filter design. In the schematics of Figure 1.1 and Figure 1.2, the path containing bold lines and configuration or devices in between represent the approach to be adopted in this research work to achieve the targeted milestone in the proposed design while the dotted line path along with configuration or devices in between are not deliberated as to be considered out of the research scope.



Fiure.1.1: Research Scope 1

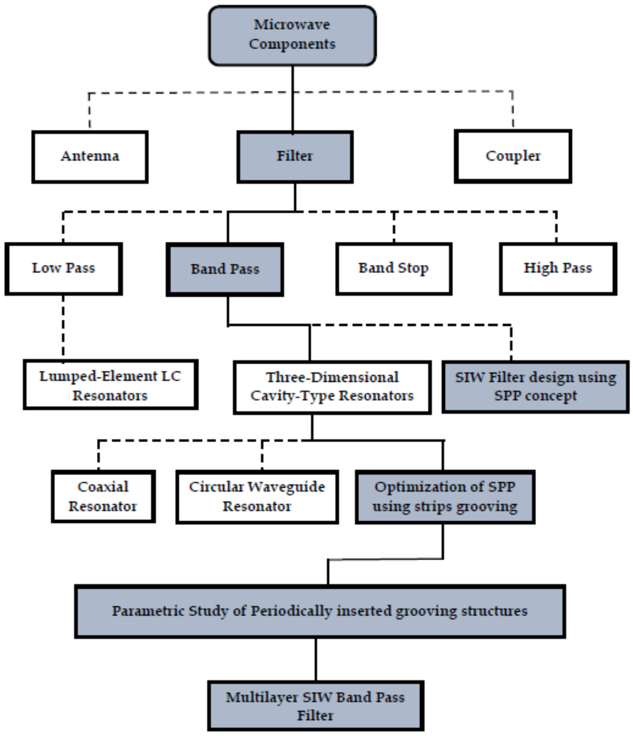


Figure.1.2: Research Scope 2

Microwaves represents the frequencies range from 300 MHz to 300 GHz in the Electromagnetic Waves (EM), with corresponding wavelengths from 1 m to 1 mm in the free space. Frequencies between 30 GHz and 300 GHz are also represented as millimeter waves. Electromagnetic Spectrum above the millimeter waves is called infrared having wavelength between 1 micrometer to 1 millimeter. Electromagnetic Spectrum consists of visible, ultraviolet, and x-rays comes beyond the infrared spectrum and radio frequency spectrum comes below the microwave frequencies.

The boundaries of frequency between the radio and microwave frequencies are somewhat arbitrary and depends on the specific technology that is developed to use the frequency in the specific range. Hence, RF / Microwave communications are used in a variety of applications but not limited to radar, navigation, sensing, satellite, telecommunication etc.

Role of Filter in Microwave Communication

The role of filters in RF/Microwave communication is very important and pave a vital contribution in the RF/Microwave applications. The filters are being used to segregate or combine the different frequencies in these RF/Microwave communication. To utilize the Electromagnetic spectrum optimally and efficiently, filters are capable in frequency selectivity to achieve the desired response.

However, due to rapidly changing technology, new applications in the Wireless Communication are emerging and imposing challenges with even more rigorous requirements in RF/ Microwave filters. These requirements include light weight, miniature size, low cost, and high-performance filters. RF/microwave filters may be implemented on the basis of distributed or lumped element circuits depending on these requirements and specifications [8].

Different realization can be designed through the implementation of various transmission line structures such as, coaxial line, microstrips, and waveguides including Substrate Integrated Waveguides (SIWs).

Application of WLAN Filters

RF/Microwave filters with low insertion loss, miniature size, and high- performance selectivity, increase development of wireless communications. A portions of radio spectrum is reserved (Industrial, Scientific and Medical (ISM)) for industrial, scientific and medical purposes other than telecommunication. A chunk of Radio Frequency Spectrum ranging from 9 KHz to 275 GHz is regulated by International Telecommunication Union (ITU). Applications used in the Wide Area Networks (WAN), microstrip filters can be the main component to select and filter out a specific band from the received free space EM waves in a WAN receiver depending upon the application. WAN receivers have variety of application such as, cordless telephones, Cellphones (1.9 GHz), Modem / Routers (2.4 or 5 GHz), Bluetooth earpiece (2.4 – 2.485), and baby monitors (49 MHz, 902 MHz or 2.4 GHz) etc.

Therefore, to select an appropriate band from incoming EM waves to any receiver, band pass filters having very accurate performance are of great importance. In addition, microwave devices including router or modems in the ISM band (2.4 – 2.5) might utilizes and emit energies in the frequency range, which can cause server interference and may distort signal completely [9]. To overcome this problem, the router / modem or device manufacturers have already taken care of this issue while incorporating a band pass filter.

In wireless LAN (WLAN) networks, WiFi is the technology that connects the electronic devices to the wireless network primarily using the 2.4 GHz (12 cm) UHF and 5 GHz (6 cm) SHF ISM radio frequency bands. To select or filter out specific band, microwave band pass filters are deployed.

Filter Classifications

Microwave filters are generally classified in to main classes:

- Active Microwave Filters
- Passive Microwave Filters

- **Active Filters**

These types of filters comprise of active components such as Op-amps and Transistors in addition to Capacitors and Resistors.

- **Passive Filters**

These types of filters comprise of passive components such as Capacitors, inductors and Resistors is called as Passive Filter. Also, structures such as conventional printed transmission lines, SIWs, and Composite Right-Left Handed transmission lines lie under the category of passive microwave filters.

For filter design, operating frequency contribute a vital role. Therefore, filters are further classified into following five types based on the operating frequency of a specific application.

- Low Pass Filter
- High Pass Filter
- Band Pass Filter
- Band Stop Filter
- All Pass Filter

- **Low Pass Filter**

This type of Filter attenuates all frequencies above cut-off frequency (fc) and pass all signals including DC [11]. These types of filters can be realized with the implementation of shunt capacitors and inductors in series or equivalent microstrip transmission line model in microwave regime.

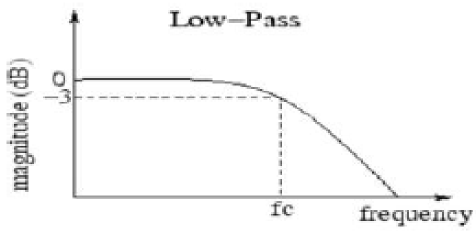


Figure.2.1: Low pass filter response

- **High Pass Filters**

This is a type of filter which suppress or cause high loss of signal below the cut-off frequencies while pass all the frequencies above the cut-off frequency. During operation of the filter, constant output or gain be achieved above the cut-off frequency.

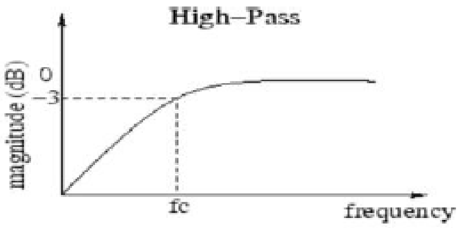


Figure.2.2: High pass filter response

- **Band Pass Filters**

This type of Filter generally consists of three frequencies i.e. lower cut-off, upper cut-off and central frequencies. The signal passes to the load during operation of the filter between the lower cut-off frequency and upper cut-off frequency. There is a central frequency between the lower and upper cut-off frequencies that is geometric mean of the lower and upper cut-off frequencies. Band pass filter will attenuate band of all frequencies below the lower cut-off frequency and above the upper cut-off frequency while pass the band of frequencies in between.

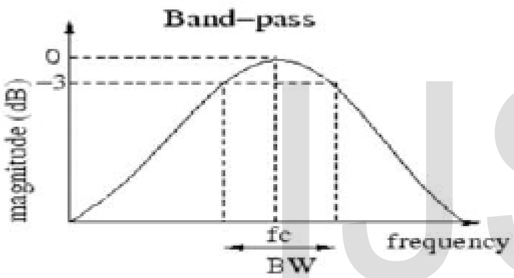


Figure.2.3: Band pass filter response

- **Band Stop or Reject Filters**

This type of filter is the complement of band pass filter. All the signal between the lower and upper cut-off frequencies will be suppressed while passing all the rest of the signal below the lower cut-off frequency and above the upper cut-off frequency. A band of frequencies will be stop between lower and upper cut-off frequencies and thus name is band reject of band stop filter.

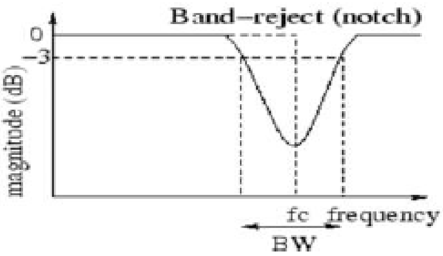


Figure.2.4: Band stop filter response

- **All Pass Filters**

This type of Filter will pass the frequencies of operation in the network devoid of any magnificent loss. The system having all pass filter is not specific to selective stop or pass band.

Keeping in view all type of filters described above, an ideal filter is the filter having perfect characteristics like no insertion loss, constant group delay over the required band pass frequencies and infinite suppression or rejection of signal elsewhere. However, in practical situations and real time environment, the filter response deviates from the parameters and characteristics of the ideal one which are the good performance measurements.

Important Performance Parameters of Filters

- **Cut-Off Frequency**

The difference between the bass-band and stop-band is determined from the corner or cut-off frequency. The -3db frequency is the frequency where the output voltage of the signal is 70.7 % of the input voltage of the signal which is also called the cut-off frequency where -3db represents half power [12]. However, at this point of the frequency the output power becomes half of the input power of the signal.
There are two following cut-off frequencies in the filters:

- **Lower Cut-Off Frequency**

The filter gain is -3db that is half at lower frequency. Lower frequency is represented by f1 and after this frequency bandpass filter pass frequency but to the contrary band stop or reject filter block the frequency after this lower cut-off frequency.

- **Upper Cut-Off Frequency:**

The output power of the signal becomes half of the input power at upper cut-off frequency. The upper cut-off power frequency is represented by f2 and after this frequency bandpass filter does not pass frequency but to the contrary, band stop or reject filter pass the frequency after this upper cut-off frequency.

- **Central Frequency *fc***

Central frequency is the frequency lies between the lower and upper cut-off frequencies of the band-pass or band-stop filters. In other words, central frequency is also the arithmetic mean of the lower and upper cut-off frequencies and can be represented as under:

$$fc=(f1+f2)/2$$

- **Bandwidth**

It is the deference between the upper cut-off and lower cut-off frequencies. In case of band-pass filter, bandwidth is the range of frequencies in which signal pass without any attenuation. In case of band-stop filter, bandwidth is the range of frequencies in which signal cannot pass and attenuated. Furthermore, the range of frequencies before the cut-off frequency is called the bandwidth in case of low pass filter whereas in case of high pass filter bandwidth is the range of frequencies after the cut-off frequency. Bandwidth of the filter can be represented as:

$$B=f2-f1$$

Classification of Filters by Response Type

Response type of the filters is categorized into number of several filter classes consisting of Butterworth filter, Chebyshev filter, Elliptic filter, Gaussian filter, Bessel filter, Linkwitz-Riley filter, Optimum "L" (Legendre) filter during the signal processing and designing phase of the filters. These classes of filter are primarily applied in designing analogue linear passive filters but the results can also be applied in implementation of digital and active filters. The classes of filters can also be derived mathematically with reference to the class of the polynomials. In the ladder implementation of the filter, the filter order can be determined from the number of elements present in the filter. Generally speaking, steeper the cut-off transition between the band pass and band stop, the higher the order of the filter [13]. In practical scenarios, there is no ideal filter with perfect characteristic and performance parameters. Therefore, the above responses of the filter are realized and in which some are good in some areas of performance parameters but poor in others.

Following brief are the well-known filters by response type:

- **Bessel Filter**

Bessel filter has approximately linear phase response in the pass band with an ideal phase characteristic. It can be used to reduce the nonlinear phase distortion. The cut-off frequency response in less sharp but has minimal phase shift.

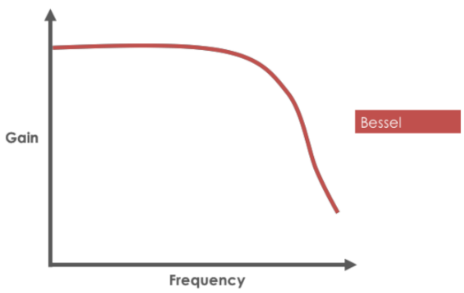


Figure.2.5: Bessel Filter Response

- **Butterworth Filter**

The approximation of Butterworth filter is also known as maximally flat magnitude response in the pass-band because it has flat amplitude versus frequency response. This type of filter approximation can also relate with the ideal filter in the pass-band. It has maximally flat response below the cut-off frequency and decreases monotonically with frequency in gain in the cut-off region. The roll-off is steepest in the pass band without pass band ripple. Moreover, Butterworth filter selectivity is far better than the other topologies of the filter responses.

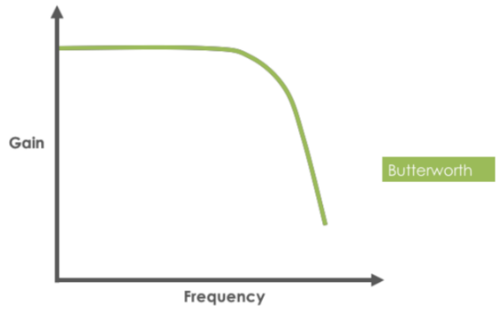


Figure.2.6: Butterworth Filter Response

- **Chebyshev Filter**

The Chebyshev filter is also called as equal ripple filter. The cut-off frequency in the Chebyshev filter is the frequency where the response decreases below the ripple band. In the passband, Chebyshev has the sharper cut-off than Butterworth filter.

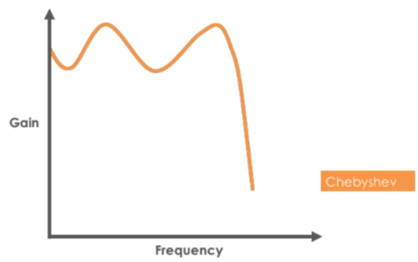


Figure.2.7: Chebyshev Filter Response

- **Elliptic Filter**

Elliptic filters contain ripple in both band pass as well as band stop region and has sharpest cut-off as compared than the other filter responses. The band pass ripple of elliptic filter is same as Chebyshev filter with improved selectivity but at the cost of complex network components.

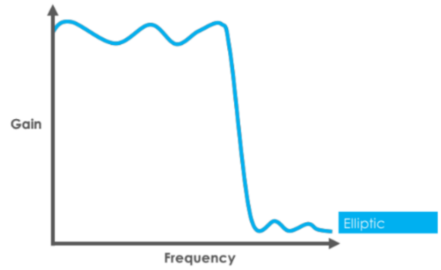


Figure.2.8: Elliptic Filter Response

Microstrip filters are one of the filters which plays a very important role in the realization of microwave planar filters. Being the most popular realization in microwave integrated and passive circuits, with the advent of 99 % pure alumina in 1960's microstrip gain rapid attention in the technology [16]. In the present time, planar filters designing and many other novel benchmarks with cutting edge characteristics are being established using novel fabrication technologies like Liquid Crystal Polymers (LCP), MMIC, LTCC, and Micro-electro mechanic systems (MEMS) etc. [17]. The realizations in filter designing with advanced properties / characteristics and optimum performance become practical and can be built with the advent of CAD tools.

Background of Microstrip Transmission Lines

In the planar transmission line structures, microstrip become the most famous which is used in Microwave Integrated Circuits (MIC). The main requirement in the microwave integrated circuits designing for a planar transmission line is the determination of characteristics on a single plane. Planar transmission line structure is the only one in which the circuit elements' characteristics can be evaluated, analyzed and determined from the single plane dimensions. Photolithographic processes can be involved in the fabrication and building of microstrip filter configurations [18]. Any discrete microwave lumped active and passive devices can be integrated easily with the help of open configuration of microstrip filter.

Microstrip consists of physical geometry with some important parameters and characteristics associated with these parameters. The geometry of microstrip transmission lines comprises of three main parts i.e. a metallic printed conductor on top, thin dielectric substrate, and ground as shown in Figure 3.1 (a). The conductor on top is having width which is represented as 'W', the substrate between the conductor and ground is having the thickness which is represented as 'h' and the 'εr' is the relative permittivity of the substance in Farads per meter (also called dielectric constant). W, h and εr are the main and important parameters associated with the geometry of the microstrip. The conductor on top is having thickness 't' can be ignored because it has insignificant importance due to its thickness 't' is approximately 10 to 20 µm [19]. As electric field lines start emerging on the side planes of this metallic conductor reside on top of the substrate. With the increase in the thickness 't' of the metallic conductor, the distribution of field changes and start more electric field lines emerging on the side planes of the top metallic line which ultimately start affecting the effective dielectric 'ξeff' as well as characteristic impedance 'Zo' of the microstrip. The thickness 't' effect is approximately about 1 % on ξeff and Zo which can be derived from the microstrip' synthesis formulas with $w/h \geq 0.1$, $t/h \leq 0.005$ and $2 \leq ξr \leq 10$ [20].

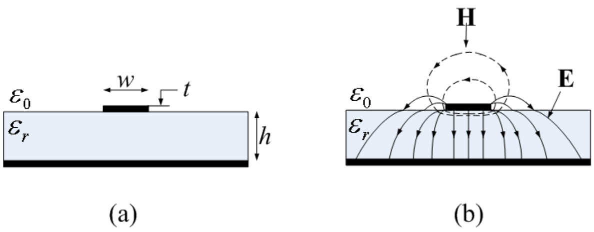


Figure.3.1: (a) Microstrip Line, (b) Microstrip Field Distributions Lines

The distributions of electric and magnetic field lines at the transverse cross-sectional plane of the microstrip are illustrated in Figure 3.1 (b). Transverse electromagnetic propagation (TEM) mode is not supported due to abrupt interface between the dielectric substrate and the air in the microstrip lines. Therefore, Maxwell's equations can be used to prove the requirement of longitude component of electromagnetic fields.

Two analysis methods can be used in determination of propagation constant and characteristic impedance of the microstrip. The analysis methods are full wave analysis and quasi static methods [21]. Analytically more rigorous and complex solutions can be provided through the use of full wave analysis method which consider the hybrid mode of propagation. The dispersive nature that is change with frequency in the phase velocity and characteristic impedance of the microstrip can be demonstrated through these methods.

Pure TEM propagation mode can be determined through quasi static method in the microstrip lines. From following two electrostatic capacitances, transmission characteristics can be found.
Ca – Capacitance per unit length, with dielectric substituted by air of microstrip line.
Co – Capacitance per unit length, with dielectric substrate of microstrip line.

Quite precise results can be achieved by using these methods up to a few gigahertzes of frequency. Effective dielectric constant expressed as under:

$$\varepsilon_{eff} = \frac{C_0}{C_a} = \frac{c}{v_p}$$

C = free space velocity
Vp = Phase velocity

Range of effective dielectric constant [20] is as under:

$$\frac{1}{2}(\varepsilon_r + 1) \le \varepsilon_{eff} \le \varepsilon_r$$

Quasi static analysis introduces the effective dielectric constant in which homogeneous medium permittivity is represented and substitutes the dielectric substrate and air in microstrip structure. The characteristic impedance Zo and phase constant β can be expressed in terms of distributed electrostatic capacitances [21].

$$\beta = \beta_0\left(\frac{C_0}{C_a}\right) = \frac{\omega}{c}\left(\frac{C_0}{C_a}\right)$$

$$Z_0 = \frac{1}{\sqrt{(cC_aC_0)}}$$

β0 = free space phase constant
W= angular frequency

In view of above all, microstrip comprises of simply a patch conductor resides on top of insulating material that is called dielectric and a ground plane at the bottom which works as the circuit common point and must be wider than the top conductor at least 10 times. Generally, at the frequency of operation, the microstrip is one half or one quarter long and equal to an unbalanced planar transmission line.

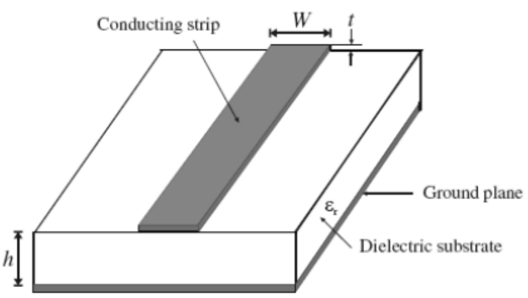


Figure.3.2: Microstrip Filter

The characteristic impedance is dependent on the physical characteristic of the microstrip line. Hence, any value of characteristic impedance between 50 ohms to 200 ohms can be realized by simply changing the microstrip lines dimensions.
The characteristic impedance of an unbalanced microstrip can be calculated by using the following equation [7]:

$$Z_O = \frac{87}{\sqrt{\epsilon + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

Zo = Characteristic impedance (Ω).
∈ = Dielectric Constant.
W = Width of copper strip.
t = Thickness of copper strip.
h = Distance between the copper patch strip and ground plane also called as dielectric thickness.

Waves in Microstrip

Microstrip fields range covers two medias above the air and below the dielectric, therefore the arrangement is inhomogeneous. Pure TEM wave propagation mode is not supported due to inhomogeneous structure of the microstrip. The propagation velocity of the TEM wave is only dependent on the material properties which are permeability (μ) and permittivity (ϵ) because the pure TEM wave consists of only transverse components. There will be longitudinal components consisting of electric and magnetic fields in the microstrip lines' waves due to the existence of two guided wave media by the air and the dielectric substrate. In this case, the propagation velocity is not only dependent on the material properties but also dependent on the physical dimensions or parameters of the microstrip [17]. The electric and magnetic field lines can be shown in below figure 3.3.

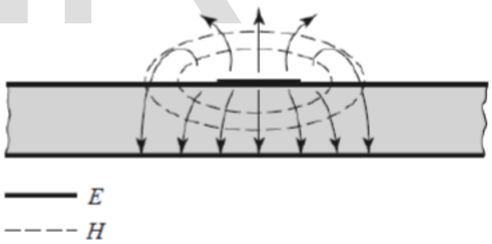


Figure.3.3: Microstrip E & H waves lines

Quasi TEM Approximation

For the microstrip line dominant mode, the longitudinal components of electric and magnetic fields remain kept very much smaller than the transverse components then these can be neglected. At this stage, the dominant mode performs similar to a TEM mode. At this point, the transmission line theory of TEM is applicable on the microstrip line theory as well and is called Quasi TEM Approximation. Quasi TEM Approximation is usable in most of the operating frequency ranges of the microstrip therefore it may also be referred as the wave propagation of microstrip has always the Quasi TEM Approximation [8].

Characteristic Impedance and Effective Dielectric Constant

The inhomogeneous air - dielectric media transformed into homogeneous dielectric material having effective dielectric permittivity in the Quasi TEM Approximation of the microstrip. Two important parameters called as characteristic impedance 'Zo' and effective dielectric constant 'ξeff' can be expressed as the transmission characteristics of the microstrip. Therefore, fine approximations and calculations for the characteristic impedance, phase velocity and propagation constant can be achieved through the analysis of quasistatic or static solutions [22]. Pure TEM propagation mode is assumed as fundamental mode in the quasistatic analysis in a microstrip.
Following expressions [23] which provide more accuracy while using very thin microstrip patch conductors i.e. t → 0, as under:

For W/h ≤ 1:

$$\epsilon_{re} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_{r-1}}{2}\left\{\left(1+12\frac{h}{W}\right)^{-0.5} + 0.04\left(1-\frac{W}{h}\right)^{2}\right\}$$

$$Z_c = \frac{\eta}{2\pi\sqrt{\epsilon_{re}}}\ln\left(\frac{8h}{W} + 0.25\frac{W}{h}\right)$$

Where, η= 120π ohms is the wave impedance in free

For W/h ≥1:

$$\epsilon_{re} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_{r-1}}{2}\left(1+12\frac{h}{W}\right)^{-0.5}$$

$$Z_c = \frac{\eta}{\sqrt{\epsilon_{re}}}\left\{\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right\}^{-1}$$

Distributed Elements – Band Pass Filter Types

There is various type of configurations of planar transmission lines for band pass filters as under:
1. End coupled
2. Parallel coupled
3. Hairpin line Filter
4. Inter-digital Filter
5. Combline Filter

- **End coupled band pass filter:**

The configuration of end coupled is shown in Figure 3.4, in which each open- end resonator is approximately the half-guided wavelength long at the mid frequency f_0 of the band pass filter. This topology has the advantage of practical realization in printed circuit technology easily and occupied less space as compared to the plain transmission line. However, there is a limitation in this type of filter configuration that its performance decreases with the increase in fractional bandwidth. Fractional bandwidth is the defined as the bandwidth of the system divided by the central frequency [24].

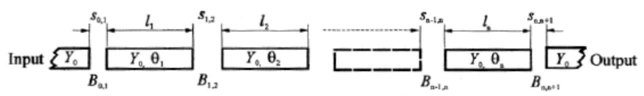


Figure.3.4: End Couple Filter Configuration

- **Parallel coupled band pass filter:**

This type of filter configuration uses half wavelength line resonators in the microstrip band pass filter realization. These resonators are placed in parallel in such a manner that half of their length are located adjacent to each other. This kind of arrangement gives large coupling relatively with respect to the given resonators' spacing in between [6]. This type of filter has fabrication ease and provide wider bandwidth.

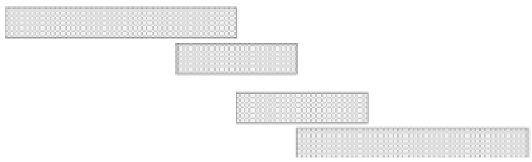


Figure.3.5: Parallel Coupled Filter Configuration

- **Hairpin band-pass filter**

This type of filter can easily be constructed by introducing short stub between the parallel coupled line resonators and merged these resonators with the stub to give "U" shaped new resonators. It can also be realized by folding the half wavelength parallel coupled resonators into U-shape. The U-shape resonator is then known as hairpin resonator. Same equations may be used in designing and synthesis of hairpin filter as for the parallel coupled line filters. However, while folding the resonator, it is required to keep the coupled line lengths short so that the coupling between the resonator can be reduced. If the two arms of the hairpin filter reside closely in the orientation, then they might be functioned as a couple of resonators and as a result maximizing the coupling between them [25]. Therefore, to employ the hairpin filter precisely and accurately, a full wave electromagnetic simulation may be utilized in the filter designing.

Figure.3.6: Hairpin Filter Configuration

- **Interdigital Band Pass Filter**

This type of filter configuration is classified as similar to the couple line filter. However, several resonators are placed in adjacent to each other alternately with one end is short and the end is open. This alternate arrangement of microstrip resonators make interdigital configuration of the filters. Each resonator is normally having quarter wavelength (λ/4). Interdigital configuration of the filter can easily be integrated with coaxial format lines and very suitable for planar transmission lines. Different coupling can be achieved by introducing different resonators physically. The fabrication of interdigital can also be done without adding dielectric support material. However, the resonators require proper grounding which is obtained by introducing the holes [26].

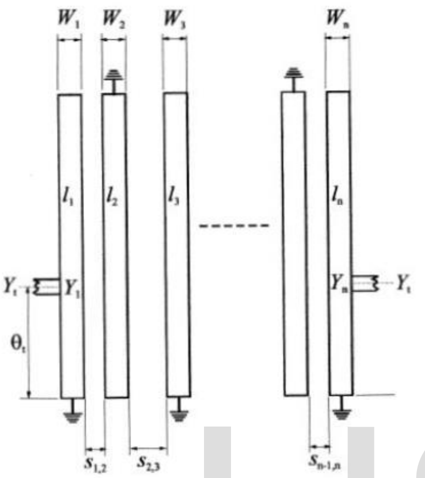


Figure.3.7: Interdigital Filter Configuration

- **Combline Band Pass Filter**

The structure of Combline filter resemble with the interdigital filter. However, the only difference in the Combline configuration is having the short-circuited ends of all the resonators at the same ends whereas interdigital configuration is alternate arrangement of short circuit and open circuit ends. Moreover, loading a capacitance is introduced between the other ends and ground of each resonator in the Combline filter configuration. Due to loading of the capacitance, the filter size can further be reduced. Proper choice of the capacitor may lead to compact resonator length. Therefore, offering enhancement in resonator length electrically while reducing the physical length. spread Same as interdigital filter, Combline filter resonators uses quarter wavelength (λ/4) [27]. Combline filters due to compactness, tremendous stop band, excellent performance and ease of tolerance in fabrication are used broadly as band pass filter in modern equipment of RF Communications.

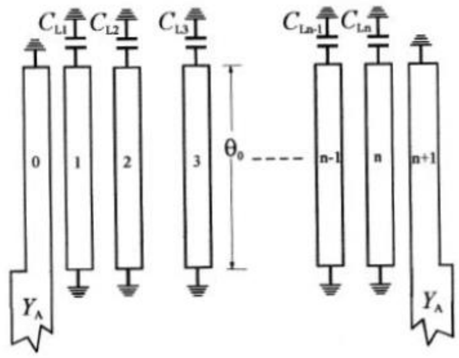


Figure.3.8: Combline Filter Configuration

The approximations of lumped element circuit in the standard circuit theory become invalid for microwave frequencies from 300 MHz to 300 GHz as the physical dimensions become impractical specifically when wavelength increasing. Due to the fact, the microwave component is normally considered as distributed circuit elements in which the physical length of the instrument significantly changes with the phase of a current or voltage. Therefore, propagation effects cannot be neglected as voltages and currents acts as waves propagation through the device [11].

A complete microwave system or circuit can be expressed in term of combination of several fundamental microwave components including but not limited to couplers, filters, power combiners and dividers, mixtures etc. However, the main objective in all these type of circuit elements or components is the capability to transmit the signal power as much as possible from one point to another point efficiently without incorporating any significant amount of loss during transmission. Consequently, it is necessary to manufacture and design the microwave fundamental devices in the shape of a guiding structure for the purpose to guide or confine the electromagnetic energy safely from one point to another with minimum loss of signal power [28].

Microstrip Filter Consideration with Limitations

Microstrip transmission lines are extensively used as guiding structure at comparatively low microwave frequencies due to its simple structure and geometry in the construction, low cost, compactness, and high ability to integrate with surface mounted components. The simple construction of the microstrip consists of a top conductor with the single ground plane at the bottom and a dielectric substrate layer in between as shown in the Figure 4.1. There are important parameters associated with the geometry of the microstrip that are width, thickness of the conductor, dielectric constant and thickness of the substrate. Moreover, the conductivity and thickness of the conducting microstrip patch or strip can also play an

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important role at higher frequencies of operation [29]. The design of printed microwave circuits, devices, and components like couplers, filters, power combiners and dividers, mixers etc. can be obtained using microstrip lines as baseline building block through careful approximations of these parameters.

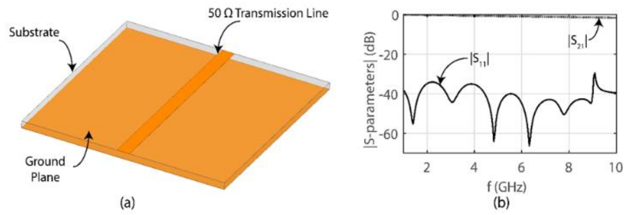

Figure.4.1: (a) Planar microstrip transmission line & (b) Magnitude of reflection coefficient showing good impedance matching & transmission characteristics over a frequency range from 1 GHz – 10 GHz.

Rectangular Waveguide Considerations with Limitations

The situation become unfavorable and changes with the increase in frequencies, as the losses in transmission lines increase with the emergent of more radiation when moved towards the higher frequencies of microwave relatively in microstrips. In this scenario, hollow pipe structures like rectangular waveguides, as shown in Figure 4.2, are preferred because such kind of structure confine the electromagnetic energy alongside waveguide and transport the energy without any significant losses, specifically at higher frequencies [30].

Hence, no radiations occur at higher frequencies in waveguides and waveguides normally contain air as a dielectric inside them. The space inside the waveguides can also be filled with dielectric material if desired. This dielectric filling results in smaller cross-sectional area as compared to the air-filled waveguides. But unfortunately, there are down sides of using hollow pipe waveguides, especially at lower frequencies especially because of their bulkiness, cost, and fabrication complexity. In addition, these structures are not easily integrate-able with the printed circuits.

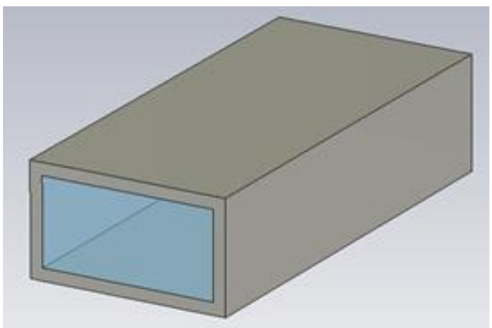

Figure.4.2: Rectangular Waveguide

Substrate Integrated Waveguide Filter

For the integration of waveguides with the printed circuits, hybrid architecture has been proposed recently between waveguides and microstrip transmission line structures which is known as Substrate Integrated Waveguide (SIW) [31]. Structure like SIW can be realized by sandwiching a dielectric material in between two conductors on top and bottom sides. Whereas, the side walls in dielectric material consist of metallic vias in the form of two linear arrays, as depicted in Figure 4.3. This hybrid technique overcome the problems associated with the individual configurations of waveguide and microstrip. SIW has the characteristics of both waveguide as well as microstrip. SIW architecture is relatively easy to fabricate, cost effective and can be easily integrated and assembled with planar printed circuits or devices as compared to the bulky waveguides. Besides, SIW provides better performance at relatively higher frequencies as compared to microstrip with minimum losses and similar dispersion characteristics as that of waveguides. Recently, significant microwave based SIW components has been reported to replace bulky waveguide and microstrip counterparts like couplers, filters, mixers, and power divider or combiners etc. at their appropriate frequencies.

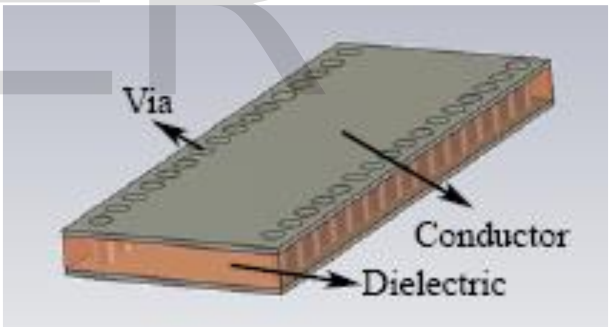

Figure.4.3: Substrate Integrated Waveguide (SIW)

Multilayer Technology

The scope of above described planar transmission line technologies is further extended with the introduction of Multilayer Technology in their applications and capabilities. In Multilayer technique, several conductor planes are stacked up with dielectric layers in between, allowing in overall size reduction of the design besides providing greater flexibility in design [32]. Moreover, it enables in enlargement of characteristic impedance realization from 20 Ohm - 200 Ohm to 5 Ohm -125 Ohm as compared to the classical microstrip line configurations [33]. In addition, it provides the greater flexibility in coupling implementation of associated various characteristics between non adjoining resonators.

Multilayer Filters

Multilayer filters have vital role in present communication systems due to enormous demand of miniature filters having cost effective, smaller size, improved selectivity and augment system performance [34]. More compactness along with the flexible design can be easily achieved using multilayer technique in the circuits. A general illustration of the multilayer Structure is shown in Figure 4.4.

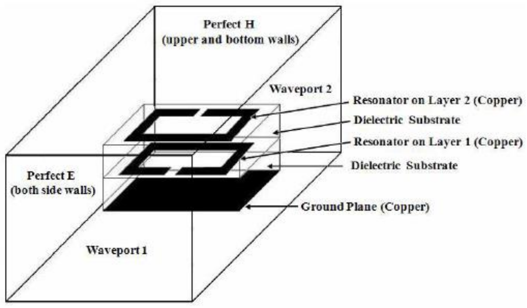

Figure.4.4: Multilayer Structure

Literature Review

The planar configuration of the transmission line band pass filters discussed above showed that to achieve reasonable bandwidth along with fabrication ease and realization of filter, different structural configuration may be adopted. Also, all possible planar configurations decrease filter size to a specific extent. This maximum limit on overall dimensions of the filter may result in the misfit of the modern communication devices having integrated WLAN chips for wireless local access. A multiband band pass filter covering WLAN band having T-shaped resonating structure is proposed in [35]. The proposed structure shows independent control of band pass characteristics over a frequency band; however, the planar configuration of the proposed design has size of 0.038 λ_g^2. Similarly, a miniaturized dual-band pass filter comprising of Stepped Impedance Resonator (SIR) and defected Split Ring Resonator (SRR) resonator is discussed in [36]. The proposed design has dimensions of $20 \times 20\, mm^2$ ($0.27 \times 0.27\, \lambda_g^2$). In [37], E- and T-shape resonator are shorted at the center to achieve filtering response at three bands (WiMAX, WLAN, and X-band). The design has overall size of $34 \times 12 \times 0.762\, mm^3$. A spiral inductor shaped and double split inductor (two) are used to develop a low loss bandpass filter [38]. For sub-6 GHz band, the proposed planar filter designs covered a chip area of $0.16\, mm^2$. Similarly, effect of defected microstrip structure shapes on performance of planar band pass filter is presented in [39]. In particular, wide band performance in band pass filter is obtained using short circuit stub topology and U-shaped defected microstrip structures. In planar band pass filters, size reduction for coupled band pass filters can be achieved using reactive loading [40]. However, the proposed miniaturization methods in planar band pass filters, miniaturize overall filter chip area up to certain level because of the fabrication tolerance, quality factor, and bandwidth.

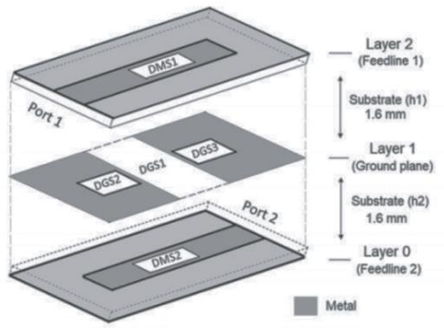

Figure 4.5: Multilayer topology of wide band pass filter having DMS and DGS [42].

Furthermore, magnetically coupled open-loop resonators in multilayer topology are used to design a dual-band balanced band pass filter [41]. The designed filter showed a narrowband response and has electrical size of 0.035 λ_g^2 @ 1.64 GHz. A tunable super wideband filter in multilayer topology having transmission lines with Defected Microstrip Structure (DMS) on separate layers with Defected Ground Structure (DGS) in between them is used for the coupling [42]. To achieve a wider band pass response, the DGS is cut into half, as shown in Figure 4.5. The use of separate ground planes results in a wideband response, however separate ground planes are preferred in the practical application. The designed filter in [42] has overall dimensions of $13.67\, mm \times 17.58\, mm \times 3.2\, mm$. In [43], a multilayer band pass filter is designed by using T-shape curved microstrip transmission lines on top and bottom layer, as shown in Figure 4.6. Whereas, circular slots in the ground plane are used for the EM coupling between the T-shaped microstrip patches. The insertion of curved T-shaped sharp edges in designed filter may arise fabrication complexities. In addition, the distance between curved T-shaped patches on a layer strongly alter the coupling characteristics of the overall filter design. In addition, dual band pass filter having multiple zeros using discriminating and source – load coupling is designed in [44]. The introduced coupling techniques improved selectivity and stop band performance. Slot coupled resonators and hairpin line resonators are used in multilayer topology to generate band pass response at 2.4 GHz and 5 GHz.

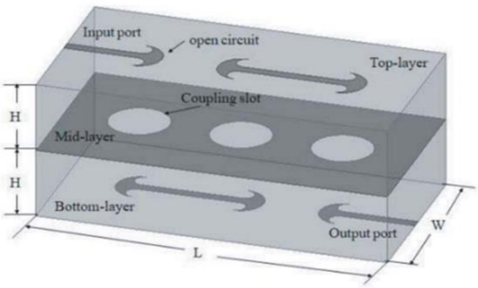

Figure 4.6: A multilayer band pass filter with circular coupling slots and T-shape curved micro strip patches [43]. H= 0.508 mm, L = 26.7 mm, W = 15 mm.

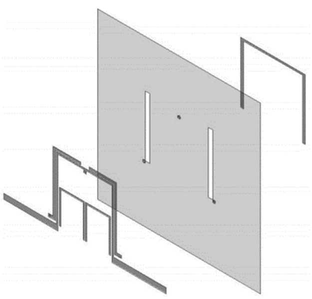

Figure 4.7: Dual Band multilayer filter design using slot coupled and hair pin resonators with slotted ground plane for coupling [44].

On the other hand, a dual-band SIW filter using complementary and open split ring resonators is proposed in [45]. An evanescent mode technique is used by etching electric dipoles (complementary and open split ring resonators) on SIW structure. The proposed design in [45] has an overall size of 0.23 $\lambda_g \times 0.13\lambda_g$ @ 2.4 GHz. The use of complementary and open split ring resonators resulted in design miniaturization but at the cost of greater fabrication complexity and narrow bandwidth. In [46], evanescent mode cavities are generated in SIW filter by loading pedestal shaped metal inserts. The metal inserts resulted in a coupled resonator filter having both positive and negative cross-couplings. An illustration of sixth order pedestal SIW filter having electric and magnetic couplings is shown in Figure 4.8. It can be observed in Figure 4.8 that increased number of vias results in greater fabrication complexity and practical realization of filter.

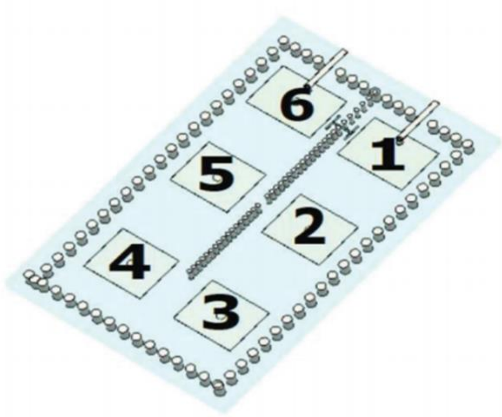

Figure 4.8: View of 6th order pedestal SIW filter.

In 2018, band pass filters are proposed by inducing Surface Plasmon Polariton (SPP) like propagation using structural dispersions in SIW [47]. Three layers of SIW are utilized in this design to achieve band pass filter based on SPP propagation. SPP break diffraction limits and localize light into subwavelength dimensions which ultimately enable strong field enhancements. The engineered SPP known as Spoof Surface Plasmon Polariton (SSPP) provide slow-wave behavior, field confinement in microwave frequency regime. In addition, SSPP presents the occurring of EM waves at dielectric and conductor interface due to strong electric and magnetic coupling. Based on SSPP, different microwave circuits such as transmission lines [47-50] and filters [51 – 57] have been proposed. Recently, electromagnetic modes are structurally dispersed in parallel plate waveguide filled with positive permittivity to achieve natural SPP concept in microwave region is proposed [58 – 59]. The occurring of SPP at interface is achieved by creating effective permittivities of opposite sign in certain frequency region by dividing parallel plate waveguide into two parts by an array of wires placed normal to the plate and filling parts with different materials. Similar method is applied in SIW structure for filtering operations at microwave frequencies [47] but with single pole in the pass band.

In view of above, there is increase trend in the utilization of multilayer band pass filter to cope up with different challenges like size reduction, better performance, and flexible design with cost effective requirements. It also provides easy integration with other microwave systems, subsystems, circuits or components. There are mainly two categories of multilayer filters [60]. First category contains coupled line resonators on different layers without any common ground in between which can be seen in Figure 4.9 (a). In this category, wide band applications are found more suitable due to strong coupling realization. Second category contains aperture couplings between adjacent layer resonators on common ground, as can be seen in Figure 4.9 (b). In this category, narrow band applications are found more suitable, However, combination of both categories is also possible [61]. Furthermore, SSPP like propagation in filters regime

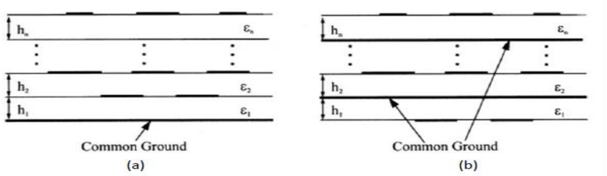

Figure.4.9: Multilayer Filter
(a) Without ground plane b/w the resonator layers
(b) With ground plane between the resonator layers.

With multiple poles in pass band in addition to the size miniaturization using multilayer topology are the major requirements of modern communication systems. This thesis is focused on the design, simulation, and realization of multilayer WLAN band pass filters using DGS structures for coupling between U-shaped resonators having open ends.

Compact and high-performance filters are required for modern communication systems. To achieve design compactness, Defected Ground Structure (DGS) are preferred [62 – 66]. The integration of multilayer technique and DGS in filter design provide significant reduction in size with an additional feature of providing strong coupling between the two microstrip lines. In addition, providing defection in microstrip structure in relation with the DGS can be used to achieve compact band pass filters. In this chapter, a multilayers WLAN band pass filter is designed using U-shaped resonators on two different layers, whereas DGS is used in between the defected microstrip structures to couple EM energy electrically and magnetically.

Design of a Planar Band Pass Filter

Initially, a planar structure consisting of ground plane with square slot is etched on the bottom side of FR4 substrate. Then, coupled U-shaped resonators behaving as a parallel LC circuit are modeled on the top layer of the substrate and connected with a 50 Ω transmission line. The width of transmission line is calculated using transmission calculator for FR4 substrate of thickness 1.6 mm and relative permittivity (ϵ_r) of 4.4. A 3D schematic of the planar band pass filter having end coupled and open stub-tapped slow wave resonators is shown in Figure 5.1. The DGS structure with square slot and U-shaped resonator behaves as a LC circuit whose values can be estimated at initial stage using [66]:

$$C = \frac{5}{\pi}\left[\frac{f_{cut\_off}}{\Delta f^2}\right],$$

and

$$L = \frac{25}{C\pi^2}\left[\frac{1}{f_{resonance}^2}\right].$$

Where, C and L are associated inductance and capacitance values, respectively. f_{cut_off} is cut off frequency of the filter and $f_{resonance}$ is resonance frequency of the filter. $\Delta f^2 = f_{cut\_off}^2 - f_{resonance}^2$.

After the optimization of U-shaped and square slots values in the ground plane, design is modeled in 3D electromagnetic simulator Ansys HFSS and values are optimized to achieve a band pass response. The results of the optimized planar band pass filter are shown in Figure 5.2. The planar band pass filter was designed on a 50 mm × 50 mm substrate.

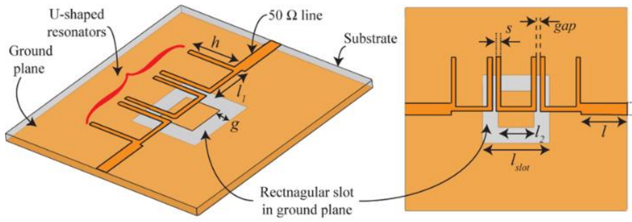

Figure 1.1: 3D and front view of Planar band pass filter having square slotted DGS and U-shaped resonator. Optimized dimensions in mm are: $l_{slot} = 15, l_2 = 8, gap = 1, s = 1, l_1 = 9, l = 10.5,\ h = 10.25, and\ g = 3.5$.

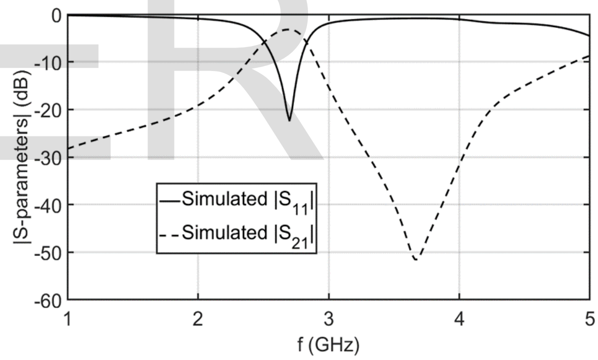

Figure 5.2: Simulated reflection and insertion loss of planar band pass filter.

It can be observed from Figure 5.1 that designed filter has 10 dB bandwidth from 2.59 GHz to 2.78 GHz having center frequency at 2.7 GHz. Whereas the insertion loss of the designed planar filter is 3.2 dB at 2.7 GHz and then increase up to 5 dB. This concludes that planar filter designed has high insertion loss because of the strong coupling between U-shaped resonators. In addition, the insertion loss response has not steep and symmetric roll-off. The coupling of ground slot for better resonance can also be observed from current distribution shown in Figure 5.3. It can be observed that maximum current in U-shaped resonator exists because of the placement of slot beneath the slot. Therefore, the placement of slot under the U-shaped resonator play an important role in design optimization.

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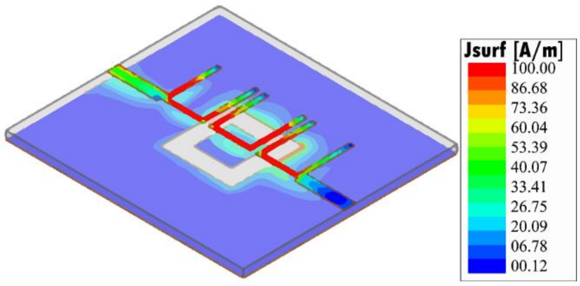

Figure 5.3: Current distribution showing coupling because of the introduced slot in the ground plane.

A parametric study on the filter design parameter was also performed to observe the effect on the insertion loss and shift of the resonance frequency. It was observed during the parametric study that changing 's' i.e. gap between U-shaped resonator greatly disturbs the reflection and insertion loss results. However, changing the dimensions of the square slot beneath the U-shaped resonator results in good reflection and insertion responses over a certain frequency range. The effect of changing 's' on insertion and reflection characteristics is shown in Figure 5.4.

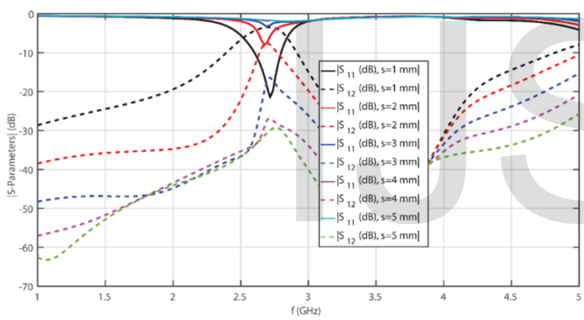

Figure 5.4: Effect of 's' on Insertion and reflection characteristics of planar band pass filter.

In addition, optimization and placement of square slot under the U-shaped resonator gap 's' also results in better insertion and reflection characteristics of band pass filter. The gap adjustment for achieving better insertion and reflection characteristics after optimizing 'gap' i.e. DGS slot is shown in Figure 5.5.

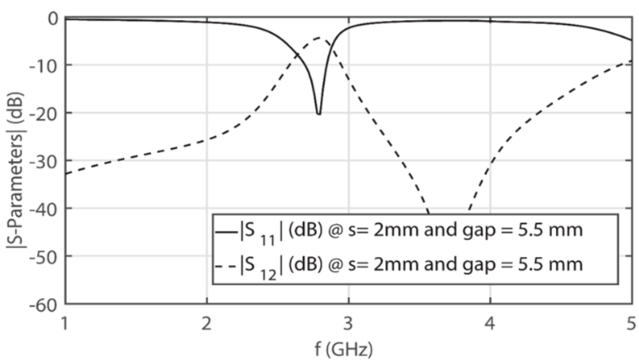

Figure 5.5: Design optimization by changing slot dimensions 'gap' for s = 2 mm to achieve better reflection and insertion characteristics.

Effect on band pass filter characteristics by changing overall width *'W'* of the substrate revealed that reflection loss ($|S_{11}|$ (dB)) remains unchanged. Whereas insertion loss ($|S_{12}|$ (dB)) increases from 3 dB to 5.4 dB because of increase in fringing capacitance due to open ends of U-shaped resonator near the substrate. This effect is shown in Figure 5.6 along with the current distribution, when 25 mm width of substrate is selected by keeping other dimensions same, as shown in Figure 5.1. Parametric analysis of the planar band pass filter also showed that filter frequency can be varied by changing the length 'h' of the U-shaped resonator by keeping in mind that good insertion and reflection losses is only achieved by optimizing the dimensions of the square slot beneath the U-shaped resonator.

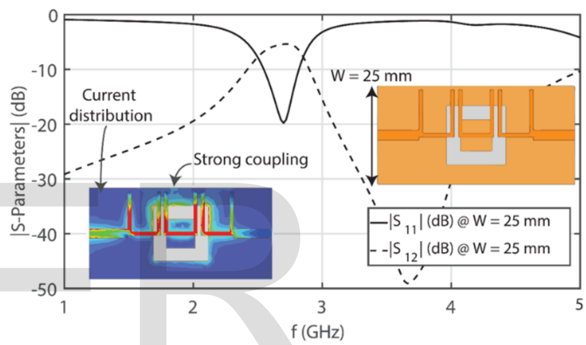

Figure 5.6: Effect of changing 'W' i.e. width of substrate. Current distribution also shown to demonstrate coupling between the open ends of U-shaped resonator and ground plane because of smaller substrate width.

It can be concluded from the parametric analysis of optimized planar band pass filter shown in Figure 5.1 that gap length '*g*' and width of the square slot '*gap*' along with the placement of the square slot beneath the resonator play an important role in achieving good insertion and reflection characteristics. For practical cases, the insertion loss should be close to 0 dB in pass band with sharp role off in the band stop region. On the other hand, reflection loss should be less than 10 dB to show that maximum EM energy is transmitted from the port to the structure. Therefore, the insertion and return loss of planar band pass filter needs further refining of results.

Design of a Multilayer Band Pass Filter

After the designing of planar band pass filter consisting of DGS having square slot and U-shaped resonating structure on top, a multilayer filter was designed and realized in simulation environment. The design and parametric study of planar band pass filter showed that size of the filter can be reduced up to a certain level as there exists a trade-off between filter performance and size miniaturization. Therefore, multilayer topology is adopted to achieve size miniaturization and enhance band pass results.

In multilayer topology, central U-shaped resonator is removed and one end of the microstrip transmission line is placed on the top side, whereas the other transmission line section is placed on the separate substrate having slotted ground plane in middle. An exploded view of the multilayer design is shown in Figure 5.7. The adopted multilayer topology resulted in decrease of size form 50 mm × 50 mm to 30 mm × 28 mm which is approximately 50 % size reduction.

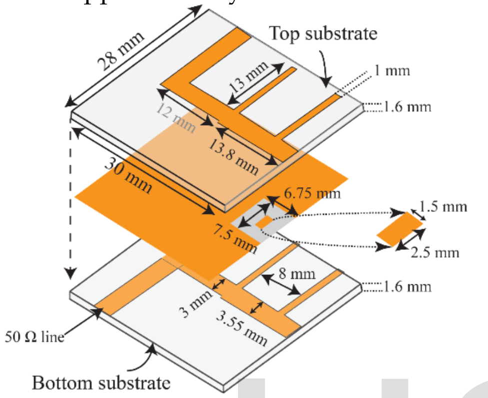

Figure 5.7: 3D and front view of Multilayer band pass filter having square slotted DGS and U-shaped resonators.

The results of reflection ($|S_{11}|$ (dB)) and insertion loss ($|S_{12}|$ (dB)) are shown in Figure 5.8. It can be observed from the results that designed multilayer band pass filter is well matched over a band from 2.24 GHz to 2.54 GHz which is enough to cover practical WLAN band. In addition, the insertion loss is close to 0 dB, as shown in Figure 5.8. The resonators' placement on top and bottom, magnetically and electrically couple fields from the U-shaped slot etched in the ground plane. The geometry of U-shaped slot is changed from rectangular slot of the planar design to further decrease the size and create strong EM coupling for the U-shaped resonators. The multilayer topology adopted in the design procedure, sharpened the transition from stop band to pass band and resulted in a good insertion loss close to 0 dB, as shown in Figure 5.8.

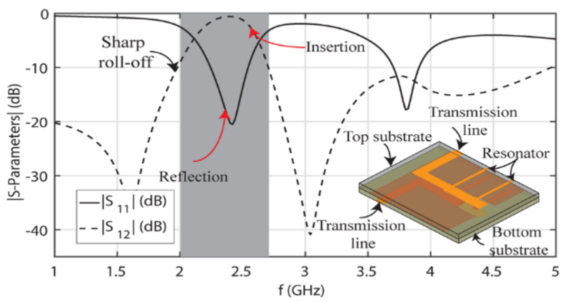

Figure 5.8: Insertion and reflection characteristics of multilayer Band pass filter.

The substrate chosen are FR4 with height 1.6 mm because of its easy availability in market. The results showed that multilayer filter suitable for integration in various WLAN systems. An illustration of current distribution in the U-shaped resonators to show the strong coupling because of the slotted ground plane the end is shown in Figure 5.9.

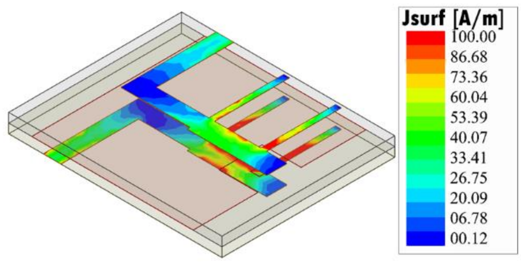

Figure 5.9: Current distribution on the multilayer band pass filter at 2.44 GHz showing strong EM coupling because of the inserted U-shaped slot placement between the U-shaped resonators.

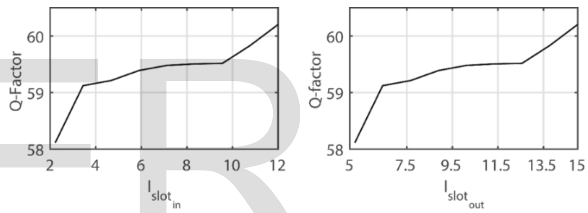

Figure 5.10: Quality factor of the proposed filter vs U-shaped slot dimensions.

Furthermore, external Quality (Q)-factor of the designed multilayer band pass filter was computed using Eigenmode analysis in Ansys HFSS and is shown in Figure 5.10. The Q-factor was calculated by changing values of lengths of ground planes lengths that are responsible for increase or decrease in the U-shaped slot dimensions and placement of the U-shaped slot. The appropriate lengths of the ground plane to change slot dimensions are clearly shown in Figure 5.11. Optimized values of the ground plane that is placed in the middle layer are also given in Figure 5.11.

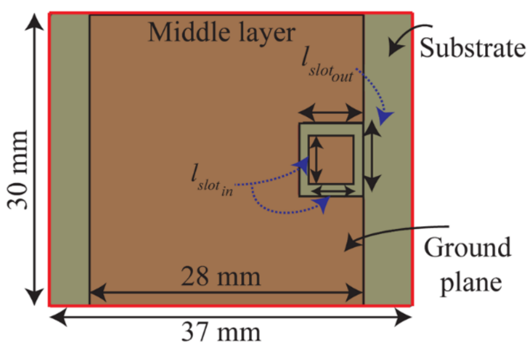

Figure 5.11: Optimized dimensions of the ground plane and parameters defining the U-shaped slot etched in the ground plane.

The E- and H-fields vector of the U-shaped slot are also computed to demonstrate the strong electric magnetic coupling. These vector plots are shown in Figure 5.12.

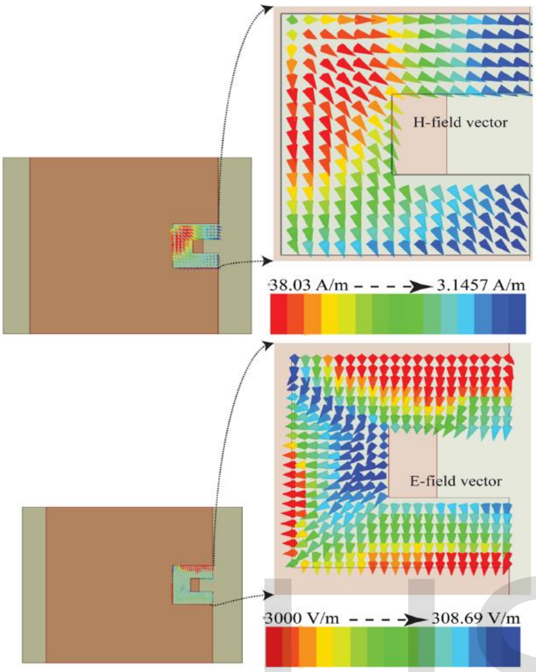

Figure 5.12: E- and H-vectors of the etched U-shaped ground plane slot showing strong electric and magnetic coupling.

Ref.	Size $\lambda_g \times \lambda_g$	F (GHz)	FBW	IL (dB)	Design Complexity
[67]	0.187 × 0.285	1.84	9.2	2.2	Medium to High
[68]	0.67 × 0.32	0.9	3.6	2.67	Low to Medium
[41]	0.237 × 0.148	1.64	8.86	0.92	High
[69]	1.23 × 1.23	3.5	3.14	1.52	High
[70]	0.417 × 0.377	2.44	8.61	1.8	Medium
This work	0.5 × 0.4	2.44	12.29	0.5	Normal

*Table 1: Comparison with reported band pass filters. *Guided wavelength (λ_g), Fractional Bandwidth (FBW), Insertion Loss (IL).*

A comparison between the proposed multilayer band pass filter with the reported work to illustrate multilayer topology benefits in the microwave filter regime. Several observations can be inferred from the comparison table based on various performance parameters.

1. **Filter Footprint:** The size of filter in terms of electrical size is shown in Table 1 with respect to the guided wavelength. It can be observed proposed filter has competent size at 2.44 GHz as compared to other reported design. Other reported filters shown in Table has their equivalent electrical size as per their frequency of operation which is less than 2.44 GHz. This low frequency of operation will result in high guided wavelength and lower electrical size at that frequency.
2. **Fractional Bandwidth:** It can be seen from the comparison table that multilayer filter proposed in this thesis has maximum bandwidth as compared to other reported designs.
3. **Insertion Loss:** The insertion loss of the proposed multilayer design is also close to 0 dB as compared to other reported designs in literature.
4. **Hardware / Design Complexity:** A comparison of the proposed design with the reported designs in terms of design and hardware complexity is also drawn. It can be noticed from the last column of Table 1 that proposed multilayer design has simple structure with minimum hardware complexity and deliver desired results for WLAN filtering in microwave systems.

WLAN band pass filter is first designed in planar topology using rectangular slot in ground plane and U-shaped resonator on the top plane. A detailed parametric study on the filter performance parameters is conducted to demonstrate the trade-offs and limitations of planar technology for size miniaturization and competent results. Then, same planar filter is designed using multilayer topology and it is demonstrated successfully that multilayer technology not only miniaturize filter size but also enhance filter results by providing strong EM coupling.

Two TE10 modes in SIW topology are coupled by designing two SIW transmission lines of slightly different cut-off frequencies. The two designed SIWs are sandwiched followed by the structural dispersion in the SIW modes to achieve a multipole bandpass WLAN filter based on SPP phenomenon.

Theoretical Analysis and Design of SIW Multilayer Bandpass Filter

Initially, two different SIW transmission lines having cut-off frequencies 4.8 GHz and 2.6 GHz are designed and optimized in HFSS. The layout of the 1st SIW transmission lines (SIW 1) with corresponding geometrical parameters are shown in Figures 6.1. Metallic conducting vias on the lateral sides of the transmission line represent SIW structure supporting TE mode. A second SIW transmission line (SIW 2) is designed on TMM10i substrate having permittivity greater than the permittivity of substrate used in SIW 1. A layout of SIW 2 with only difference in width is shown in Figure 6.2. All of the geometrical parameters of both the SIW transmission lines are kept same except the width of the SIW because cut-off frequency of dominant TE10 mode depends on widths a1 and a2. The widths of the SIW section i.e., a_1 and a_2 are calculated using (6.1) to design two SIWs having slightly different cut-off frequencies.

$$f_{cutt_{off}} = \frac{c}{2a_i\sqrt{\epsilon_r}}, \qquad i = 1, 2$$

The results of the first SIW transmission line having 4.8 GHz cut-off frequency are shown in Figure 6.3. It can be inferred from Figure 6.3 that designed SIW is supporting EM wave transmission from 4.8 GHz. Also, E-field distribution shown in inset of Figure 6.3 further confirms that above 4.8 GHz basic and fundamental mode i.e., TE_{10} mode is present. The SIW 1 is designed on FR4 substrate having thickness of 0.769 mm.

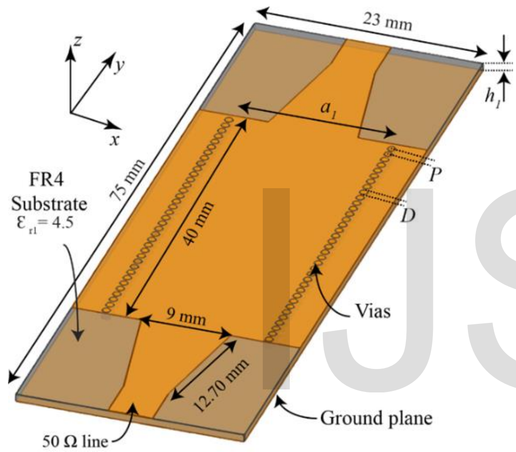

Figure 6.1: Layout and dimensions of SIW transmission line designed on 0.769 mm (h_1) FR4 substrate having a_1= 18.8 mm.

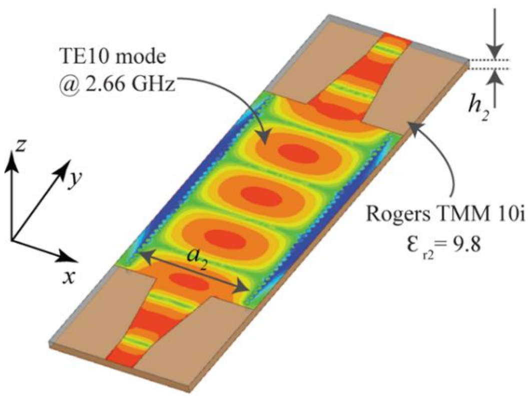

Figure 6.2: Layout of SIW 2 designed on Rogers TMM10i substrate having thickness 1.27 mm (h_2) and a_2 = 15.6 mm.

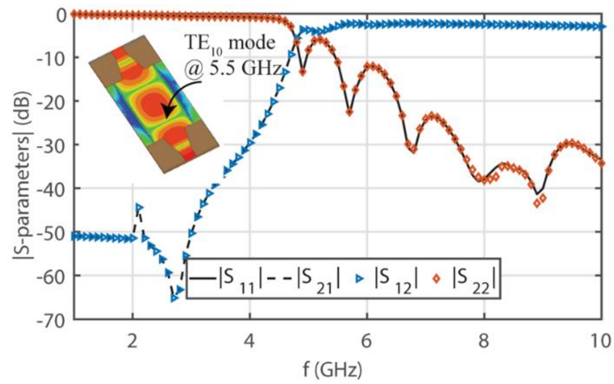

Figure 6.3: Results of SIW transmission line designed on FR4 substrate showing 4.5 GHz cut-off frequency with dominant TE_{10} mode.

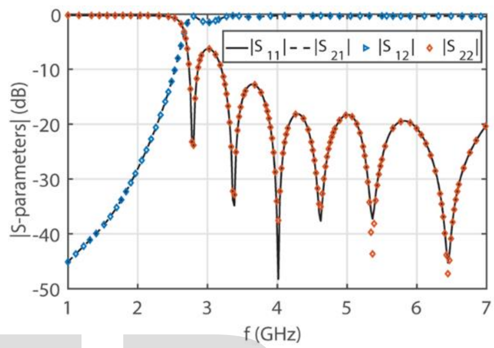

Figure 6.4: |S-parameters| (dB) results of SIW 2 showing 2.66 GHz cut-off frequency.

Similarly, second SIW transmission line (SIW 2) on 1.27 mm thick TMM10i having cut-off frequency of 2.5 GHz is also designed and shown in Figure 6.2. After designing two separate SIW transmission lines with different cut-offs, SIW 2 shown in Figure 6.2 is placed on the top of SIW 1 shown in Figure 6.1. Only SIW section of SIW 1 without any microstrip is placed, whereas the feed is applied only at SIW 2, as shown in Figure 6.5. The results of the corresponding design in Figure 6.4 show that because of higher permittivity and lower width $a_2 = 15.6\,mm$ as compared to SIW 1 ($a_1 = 18.8\,mm$), cut-off frequency move down to 2.66 GHz. The corresponding results of the multilayer topology depicted in Figure 6.6 show that instead of broadband transmission over a large frequency range, narrow band transmission of EM wave a certain frequency range exist. However, there exist losses in the transmission as |S21| (dB) goes below -3 dB at certain frequency ranges.

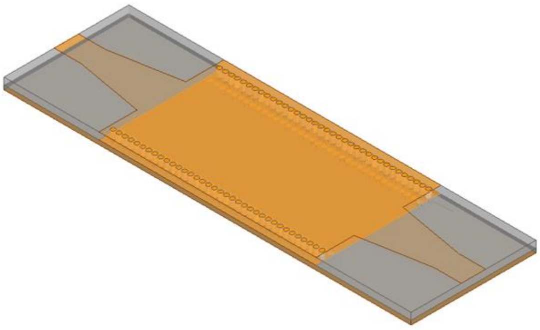

Figure 6.5: Multilayer topology of two SIW transmission lines (SIW 1 and SIW 2) having different cut-off frequencies.

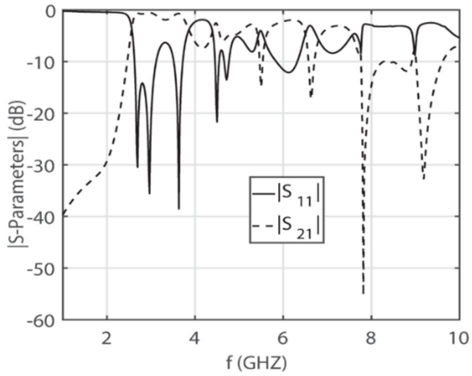

Figure 6.6: |S-parameters| (dB) characteristics of multilayer topology of SIW 1 and SIW 2.

Next, to achieve a bandpass response with sharp cut-off frequencies, cross structures are incorporated in the SIW transmission designed on FR4 substrate to create structural dispersions in the overall structures. These geometrical modifications resulted in effective dielectric constants (ϵ_{eff}) of opposite signs having coupled TE_{10} because of the two SIW transmission lines i.e., SIW 1 and SIW 2 in a certain frequency range. In other words, this phenomenon further results in the field confinement at certain band of frequencies and helps in achieving SPP like propagation at the SIW transmission lines' interface in a certain frequency range to create a band pass spectral response. The frequency range of band-pass filter in sandwiched SIW structure with structural dispersion can be effectively controlled using relative permittivity of substrates and width of the SIW transmission lines (a_1 and a_2 in our case), as evident from relation given below [71]:

$$\epsilon_{eff} = \epsilon_r - \left(\frac{c}{2af}\right)^2.$$

In the finalized design, SPP like propagation was achieved by inserting novel crossed slots in SIW 1 to create structural dispersions in the SIW structure. The dimensions of these crossed slots with complete multilayer layout are shown in Figure 6.7. A drawing of the final design with complete geometrical dimensions are also shown in Figure 6.7. Quality factor of the filter is also shown in inset of Figure 6.7. It can be observed form Q-factor plot that the proposed geometry has high Q-factor. Also, value of Q-factor depends on the length of crossed slots. The effective dielectric constant with respect to frequency and frequency vs wavenumber graph are shown in Figure 6.8 to verify the design principle, frequency range of bandpass filter, and SPP like propagation.

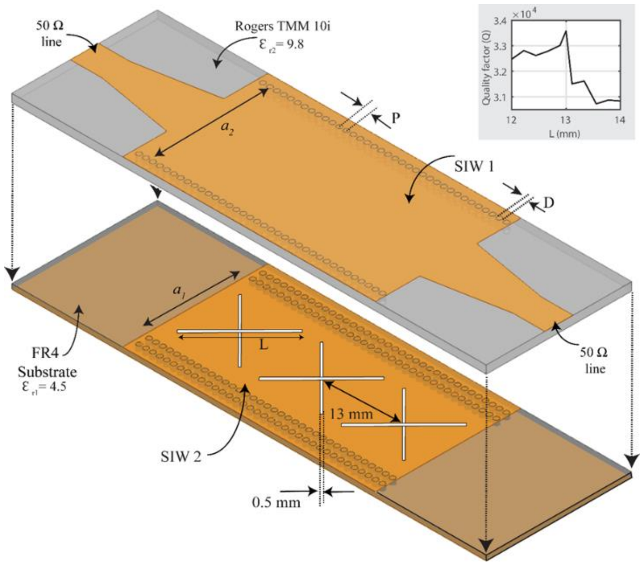

Figure 6.7: Layout of SIW multilayer filter having SPP like propagation and geometry of crossed slots for structural dispersion. P = 1.1 mm, D = 0.8 mm, a_1 = 18.8 mm, a_2 = 15.6 mm, L = 14 mm.

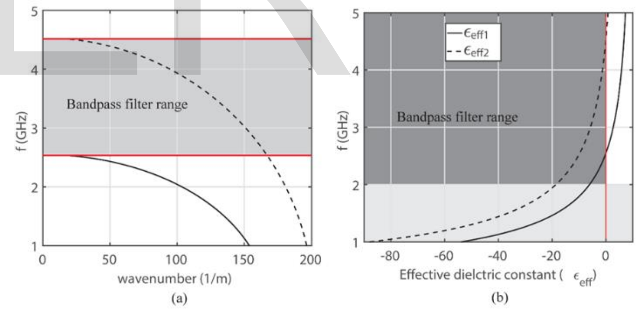

Figure 6.8: (left) Frequency range of bandpass filter depending upon the widths of SIW and according to opposite signs of effective dielectric constant in multilayer topology of SIW 1 and SIW 2. (Right) Dispersion curve of the proposed multilayer SIW filter having SPP like phenomenon and showing bandpass filter frequency range.

The magnitude of S-parameter results of the final optimized multilayer design are shown in Figure 6.9. It can be observed from the Figure 6.9 that proposed design has good band pass characteristics and spectral response from 2.48 GHz – 3.05 GHz. The insertion of the proposed filter is near to 0 dB over the band of interest. In addition, a symmetric roll-off exist in the spectral response with good impedance matching characteristics over the band of interest. In inset of Figure 6.9, disturbed TE_{10} mode is also shown along with the multilayer topology of two SIW transmission lines. The E-field distribution shown in inset of Figure 6.9 demonstrate that the structural modification by inserting crossed slots in multilayer SIW topology alters the E-field response as compared to the E-fields shown in inset of Figure 6.3 and Figure 6.2.

Furthermore, an eigen mode analysis of the proposed filter was also conducted to observe the Q-factor of the proposed filter. The results showed that because of inherited proposed of SIW for high power handling capabilities, the Q-factor of the proposed filter at optimized dimension shown in inset of Figure 6.7 and is about 33121.

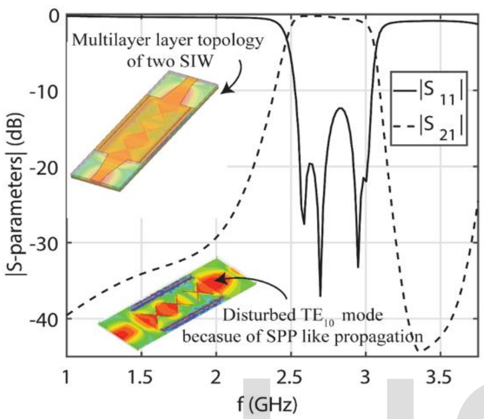

Figure 6.9: Spectral response of multilayer SIW bandpass filter having SPP like propagation.

To confirm and validate the SPP like propagation because of the crossed slots insertion, E-fields in yz and xy plane are also plotted and depicted in Figure 6.10. If Figure 6.10, E-field of multilayer SIW topology without insertion of cross slots is also to provide comparison between the inserted cross slots and without crossed slots. The comparison verified that insertion of novel crossed slots confined E-field at the interface of two SIW transmission lines and resulted because of opposite signs of effective dielectric constant. This arrangement allows SPP propagation at the interface of two SIW transmission lines. In addition, using different widths of SIW transmission lines and carefully selecting high or low permittivity substrates, variable frequency ranges having bandpass filter response and desirable signs of effective dielectric constant can be tailored. Moreover, the E-field distribution showed that at band-pass frequency, maximum field is confined at the SIW interface and increase in propagation constant (β) to result in more than one pole spectral response.

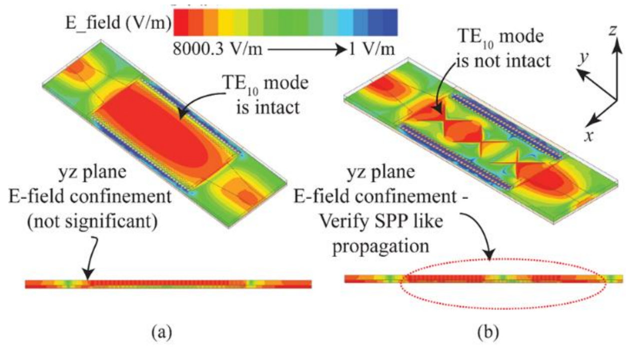

Figure 6.10: E-field distribution of multilayer SIW band pass filter designs with and without cross slots to demonstrate SPP like propagation.

Moreover, to understand the band-pass spectral response of the proposed structure because of crossed slots, a parametric study on the dimensions of the crossed slots is also carried out in this research. The results of the corresponding variations in crossed slots are shown in Figure 6.11. The parametric study showed that the length of the crossed slots (L) is the main controlling parameters to change the spectral response and proper shaping of the band pass filter. Other than this, the frequency band of band pass filter can be further controlled by changing the cut-off frequencies of the incorporated SIW transmission lines by keeping in mind the opposite effective dielectric concept discussed earlier in the light of Equations (6.1) and (6.2). However, the period of the inserted vias on lateral sides of the SIW greatly influence the guided EM wave. An increase in vias period from an optimized value may introduce leakage of EM waves from lateral sides and result in a travelling antenna such as leaky wave antenna [72] instead of filter.

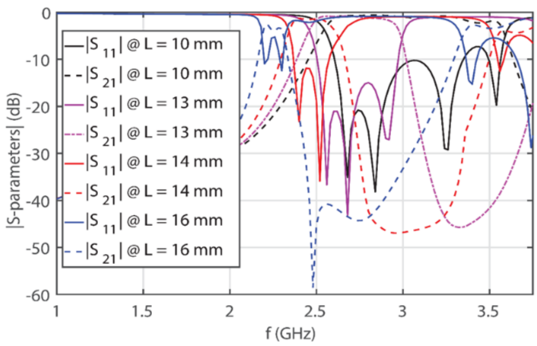

Figure 6.11: Parametric study to observe the change in spectral response of the proposed multilayer bandpass filter.

Conclusions

In this research work, the researcher has presented in detail the background and literature review of Microwave Filters for WLAN applications. Miniaturized and compact size filters along with high performance are always be the attention for new technologies. However, the first filter design is proposed on single planer topology having compact size (50 mm x 50 mm). The geometry of the design consists of Defected Ground Plane (DGS), Substrate and three U-shaped hairpin resonators on top of the substrate. This proposed design covers the frequency band from 2.59 GHz to 2.78 GHz having central frequency at 2.7 GHz with insertion loss 3.2 dB up to 5 dB. Furthermore, better results of return loss and insertion loss can be achieved by changing the physical parameters in the proposed designed.

Research work is further enhanced by proposing another novel design of multilayer bandpass filter with more compactness and higher performance. The size is 30 mm x 28 mm which is approximately 50% reduction in size as compared to the planar geometry. This proposed filter design operates over the frequencies from 2.24 GHz to 2.54 GHz having central frequency at 2.44 GHz with insertion loss of 0.5 dB. Finally, optimized, miniaturized and high performance requirements is achieved in this work for variety of WLAN application.

In the end, novel multilayer SIW bandpass filter from 2.48 GHz to 3.05 GHz is proposed. The simulations and design optimization were carried out full-wave 3D electromagnetic software Ansys v. 2016.2. The bandpass filter is realized on Substrate Integrated Waveguide (SIW) that consists of two SIW structures. The two SIW structures are first designed separately with different cut-off frequencies. Then, the two SIW structures are placed in multilayer topology. Crossed slots are etched on SIW 1 to achieve effective permittivities of opposite signs in certain frequency range. It is concluded that such configuration result in SPP like propagation and provide bandpass filter response. A detailed description of numerical results further demonstrated that careful selection of parameters and permittivity of SIW substrates can effectively shift the spectrum of bandpass response. It is also concluded that proposed multilayer SIW bandpass filter having SPP propagation provide flexible of pass bands and have high Q-factor. In addition, the realization of these filters is very straightforward which increases its employability in filtering applications.

Future Recommendations

- The proposed filter design can be further fabricated.
- The filter geometry can be further optimized for future generation wireless technologies.
- Owing to the resource limitation because of COVID – 19, one of the future work can be the fabrication and measurements of multilayer bandpass filters proposed in this thesis. Another future avenue can be design and analysis of dual or triple band pass multilayer filter design for multiband pass filtering applications. Reconfigurable or tunable multilayer bandpass filter design is also very promising future research direction that can be explored.

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