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Diplexer design for 4G Mobile Communication using Distributed Component Filters

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ABSTRACT

In this paper, various distributed components band pass filters for the diplexer design were investigated to operate for the multi- bands of the LTE antenna i.e. 698 – 960 MHz and 1710 – 2700 MHz. The main aim behind the design of the diplexer was that there is a need to reduce the size of the diplexer without compromising the performance of the diplexer to a greater extent. In contrast to this, high degree of miniaturization was accompanied with great deal of degradation in the performance of the diplexer.

KEY WORDS: Filter Design, Diplexer Design, Stub Filter, Coupled Line Filter.

I. INTRODUCTION

The 4G (Fourth Generation) mobile communication has recently been the focus of intense research in developing its standards, features and applications that would exceed those of 3G while keeping the communications device size compact. This would, in turn, impose high demands on the design of the handheld device; in particular, design of the transceiver since its size controls the overall device size. This work is focused on investigating the various filters design techniques for the miniaturization of the diplexer without compromising the performance of the diplexer to a greater extent.

A diplexer is an important part of the transceiver circuit as it allows the signals from multi-band LTE(Long term evolution) antenna to be separated and processed by two separate receivers at the same time to achieve the high data rate requirements of the 4G network. It consists of three ports of which P1 (Port 1) is for the input or in other words, it is the common port, whereas, P2 (Port 2) and P3 (Port 3) are for the splitted subbands respectively [1]. The main function of the diplexer is to separate the signals for the upper and lower LTE frequency bands from the combined spectrum of frequencies at the common port of the diplexer and make them available on the two output ports with minimum leakages between them. This inturn supports the parallel processing of the signals for the lower and upper frequency passbands. In this case the upper and lower LTE (Long Term Evolution) frequency bands i.e. 698 – 960 MHz and 1710 – 2700 MHz are to be split from a combined frequency spectrum.

Rest of this paper is divided into the following parts. Section II shows the background of this work. Section III is describing the motivation for this paper. Section IV represents the filter design technique and their tradeoff, size and performance. Section V explains in detail our proposed stub filters based diplexer design. Section VI concludes our work and specifies the future work that can be done for miniaturization, while maintaining acceptable performance of the diplexer.

II. BACKGROUND

4G is the future of mobile communication and it is expected to replace the existing 3G (3rd Generation) networks completely in the next few decades. It is designed to provide high speed and multimedia services based on IP (internet protocol). 4G would be an integrated global network that would allow voice, data, and streamed multimedia to be available to the users anywhere and at any instant of time at high data rate. Fig. 1 shows that 4G systems are going to incorporate all the systems from different networks i.e. different private, public, personal area, operator based and adhoc networks and would be an IP based integrated system [3].

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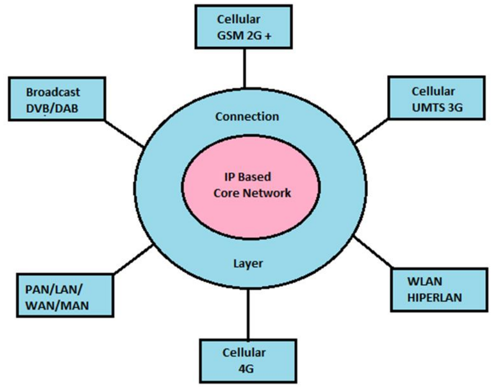


Fig. 1. Seamless connections of networks [3].

The multiplexer is an important part of the microwave front end as it is used for the separation of channels which are used in various applications i.e. radar, transceivers etc. The multiplexer give different frequency bands to every channel so that it can operate at high bandwidth [5]. One of the well known multiplexer is a diplexer which multiplexes a combined spectrum of frequencies into two sub-bands.

The dual frequency band operation in the latest communication systems requires a diplexer to be used in the design of a transceiver so that a single antenna can operate at two different frequency bands to both transmit as well as receive. To fulfill the high requirements of the latest transceiver design the diplexer should be planar and compact [6]. Diplexer is a three port device that separates two frequency bands from a combined frequency spectrum and makes them available on the two output ports while keeping the interference between the signals to the minimum and the two ports can be fed to two different receivers for parallel processing [8].

The design of a diplexer involves two different filters with respective frequencies having distinctive non-overlapping pass bands. If the pass bands of the filters are close to each other there will be an adverse effect on each other due to that. This detrimental effect will cause the return loss to decrease and insertion loss to increase where as destroying pass band's symmetry and flatness [8].

Most widely used diplexer for wireless communication consists of two bandpass filters, however, the main hurdle in the design of the diplexer is that it's size is never small enough [9]. On the other hand the modern trend in the design of the diplexer is to achieve high performance while keeping the cost and size to minimum. Bandpass filters are a good choice to achieve this because they can be fabricated on a dielectric substrate with low cost [10]. An increase of sections in diplexer help in increasing the bandwidth of the passband causing increase in losses as a tradeoff [12].

III. MOTIVATION

As the users of the wireless handheld devices have grown rapidly during the last decade there is an ever growing demand for higher data rates and increased features & applications available in modestly sized communication devices. The endeavor of the future 4G network is the flawless connectivity of the user of handheld terminals anywhere and at any time. This puts high demands on the diplexer hardware so that it can allow the handheld devices to operate at different frequency bands in a heterogeneous network. The diplexer plays a vital role in the reduction of the size of the handheld terminals by reducing the transceiver's circuitry. The dual band operation of the multi-frequency LTE antenna requires a diplexer which is used for multiplexing the received signals into two different receivers based on their frequency. The diplexer has been researched at large since 1960's because they are indeed a vital part of communication [2].

In [4], a fully integrated planar triplexer using microstrips for multiband UWB has been presented. Three flat sub-bands in the frequency band 3.1–4.8 GHz for multiband UWB have been achieved. The triplexer can be integrated into a printed circuit board using a commercial process technique at low cost, even though the guard-band has only a relative bandwidth of 0.7% between the three subbands. The triplexer uses three filters with a combined broadside- and edge-coupled structure. Keeping in sight the functionality, the diplexer and triplexers are similar and the only difference in diplexer design is that it has one output port less than the triplexer. In the diplexer design, two filters are used for splitting the upper and lower frequency passbands of the combined spectrum [8].

Broadband antennas are very useful in many applications because they operate over a wide range of frequencies. Debalina Ghosh' et al. [3] deals with ways of converting various resonating antennas to traveling-wave antennas by using resistive loading. Appropriate loading increases the bandwidth of operation of the antennas.

Hence, the transient responses of these antennas can be used to determine their suitability for wideband applications with a low cutoff frequency. Authors also illustrates the radiation and reception properties of various conventional ultra-wideband (UWB) antennas in the time domain. An antenna's transient response can be used to determine the suitability of the antenna in wideband applications.

In [5] a miniaturized microstrip triplexer with a common resonator section is proposed. Triplemode SIR design graph is also provided to design the common resonator. In addition, extra transmission-line matching network connecting three filter channels is not needed in our triplexer design. In comparison with the conventional triplexer, the proposed one has more compact size because an extra matching network and two resonators are saved.

A compact diplexer with very high output isolation is proposed by using hybrid resonators [6]. Both the adjacent channel suppressions and isolation are better than 55 dB. This diplexer can be used in the dual-band personal communication system.

In this paper [7], a new type of diplexer is presented. The simulated data show that the micro-strip diplexer has excellent performances of low insertion loss and wider suppression band-stop [13]. Also, the second harmonic falls into the stopband and can be suppressed directly. The diplexer can be used in the satellite communications system.

In this study [9], the dual-bandpass filter is realized using parallel coupled microstrip lines and open-loop stepped impedance resonators (SIRs) loaded with two shunt open stubs, and the matching circuits are developed based upon the single-shunt-stub tuning and the double-shunt-stub tuning which is called π type circuit. The diplexer is designed to support dualband operation at 2.4-2.5 GHz and 4.9-5.8 GHz frequency bands which are used in WLAN applications.

A compact diplexer using a square open loop with stepped impedance resonators is proposed in this paper [10]. The resonator consists of two identical patches which are attached to the inner corner of the square open loop. The bandpass filter and diplexer are used as alternative techniques for the implementation of transmission zeros using an asymmetric feed structures.

IV. FILTER DESIGN

The design of the diplexer principally requires the design of two filters which will work on the upper and lower frequency passbands of the LTE. These filters can be designed using various distributed components filter design technique i.e. coupled line filter and stub filter which are explained in this section with the aid of simulation results.

A. DESIGN SPECIFICATION

The requirement of the 4G diplexer design is that two filters for the LTE upper and lower frequency passbands i.e. 698 - 960 MHz and 1710 - 2700 MHz at minimum -3 dB attenuation should be designed and combined together along with their matching network in each filter branch. The specification for the response of the filters is that the steepness of the transition band should be more than -40 dB and the input reflection (S11) should not be more than -6 dB.

The ADS (Advanced Design System) 2009 from Agilent Technologies Inc. software tool was used to analyze and optimize the simulations of the designed filters. The design process consists of three main steps i.e. use of a simulation tool i.e. ADS to make the schematic of a filter and to optimize it to get the simulation results according to the diplexer design requirements. The second step involves the layout generation using the momentum tool available in ADS and its optimization. The final step is to integrate the filters for designing a diplexer along with their matching networks and to make a PCB of the diplexer using RO4360 substrate, see Table 1 for substrate definition and perform measurements by using available Rhode and Schwartz ZVM vector network analyzer.

Following are some of the features which make RO4360 substrate ideal for this design [17]

- It is the most balanced material with regards to performance and ease of processing.
- It has the "glass reinforced, hydrocarbon filled ceramic material with high thermal conductivity" and having minimum losses.
- It excels over all other RO (Rogers) substrates as it is lead-free which makes it more environments friendly.
- It has better rigidity which makes it's processing better for use in multilayer PCB fabrication while keeping the costs low.
- It has more design flexibility and the plated through holes are more reliable.
- It has Dk (dielectric constant) of 6.5 which helps the RF designers to reduce the size of the circuit [15].

Table 1: Substrate Definition

Parameter (Rogers 4360)	Dimension
Relative dielectric constant	6.15
Substrate thickness	0.305 mm
Metal thickness	18 µm
Loss factor	0.003
Metal conductivity	5.8×10^7 S/m
Conductor surface roughness	0.001

A. COUPLED LINE FILTER

The narrow band bandpass filters can be made by cascading coupled line sections, a two port network is formed by opening or shorting two of the four ports which provides 10 possible combinations out of which few are for different filter responses mentioned in the lumped components [12]. The coupled line filter provides a frequency response between its input and output ports which are bandpass if the P2 and P3 are left open and P1 and P4 are used for cascading with the rest of the coupled line sections as shown in fig. 2.

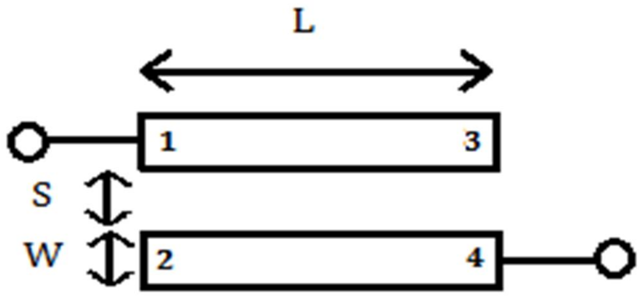


Fig. 2. Coupled lines section [15].

i. SIMULATION RESULTS

The distributed component filter design was initiated with a design of 5th order bandpass filter with butterworth response for lower frequency band by means of the coupled lines sections. Fig. 3 shows the schematic diagram of the 5th order bandpass filter with butterworth filter response and it was designed in ADS utilizing 6 coupled line sections.

It is important to mention here that N (number) coupled line sections provide N-1 order response and additional sections are used to make transition band steeper. Further increase of sections help increase the bandwidth of the passband causing increase in losses as a tradeoff [12].

It can be seen from Fig. 3 that there are three parameters associated with each coupled line section i.e. l (length), w (width) and s (spacing) for its bandwidth tuning. Table 1 shows that l which is the length of the coupled line section is maximum 49.932 mm and minimum 49.090 mm and it is repeated 6 times making the length of the filter long. The w of the transmission line section of the coupled lines section has the minimum dimension 0.105 mm which is too small to be fabricated. The third parameter s which is the spacing between the coupled lines is also very small with minimum spacing 0.031 mm which is also too small for the PCB lab to be fabricated, infact the minimum limit to the dimensions is 0.254 mm which can be fabricated [17].

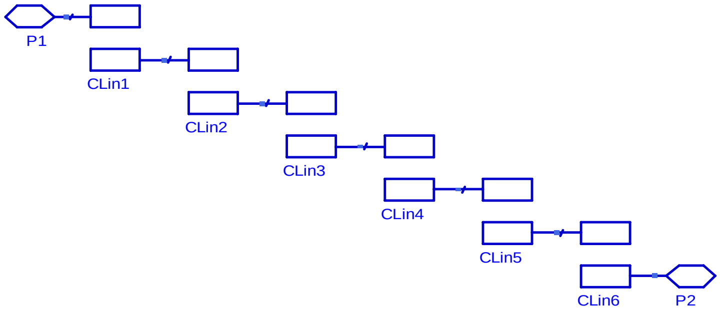
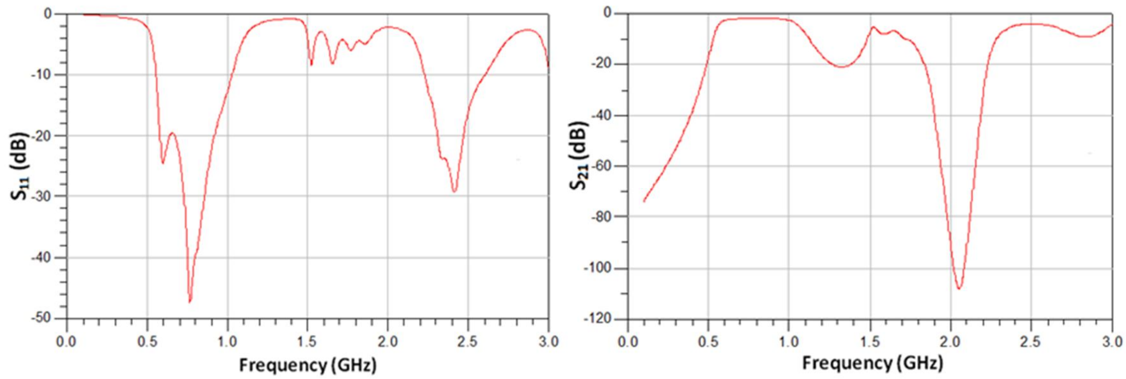


Fig. 3. Schematic of a 5th order coupled line bandpass filter with butterworth response for lower frequency band.

Table 1: Lower frequency band coupled line filter parameters

Cline (N)	*l* (mm)	*w* (mm)	*s* (mm)
1	49.932	0.105	0.033
2	49.570	0.156	0.031
3	49.090	0.230	0.038
4	49.090	0.230	0.038
5	49.570	0.156	0.031
6	49.932	0.105	0.033

Fig. 4 (a) shows the schematic level simulation result of the 5th order coupled line bandpass filter with butter worth response for lower frequency band having input reflection S11 of -20 Db, which fulfills the design specification. On the other hand fig. 4 (b) shows the simulation result of the forward transmission i.e. S21 of this filter having a passband of 592 – 1011 MHz, which is 60 % greater than the LTE upper frequency band specification.



(a) (b)

Fig. 4. Schematic level simulation results of the 5th order coupled line bandpass filter with butterworth response for lower frequency band: (a) input reflection S11, and (b) forward transmission S21.

In the second phase of the coupled line filter design, the bandpass filter was designed for the upper frequency band similar to the way it was designed for lower frequency band. Fig. 5 shows the schematic of the coupled line filter for upper frequency band, which shows that the order of the filter was incremented to 7 indicating the increase in size of the filter. However if the same parameters are considered which were mentioned before in the case of lower frequency band filter i.e. l, w and s the feasibility of fabrication can be investigated. It can be noticed from Table 2 that the design parameter l has maximum value 19.563 mm and minimum value 18.672 mm i.e. it is decreased to less than half the value for lower frequency band coupled line filter design. The parameters w having minimum dimension 0.040 mm and s having minimum dimension 0.032 mm are both too diminutive to be fabricated in the PCB lab.

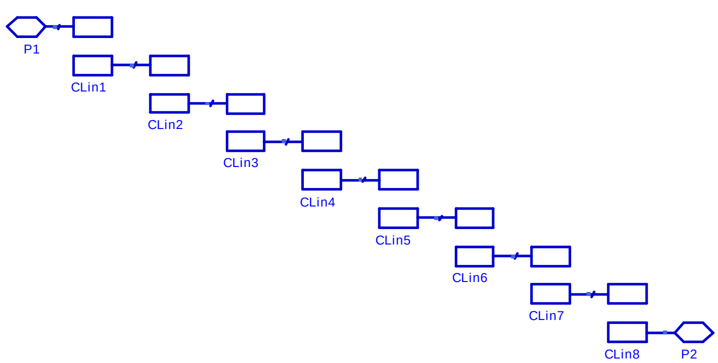
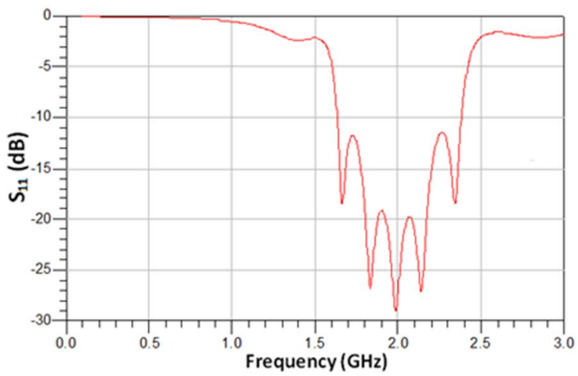


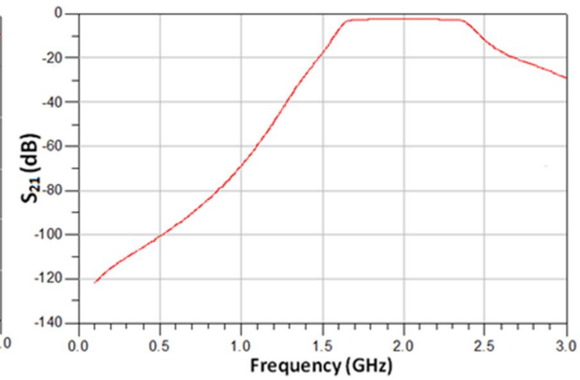
Fig. 5. Schematic of a 7th order coupled line bandpass filter with butterworth response for upper frequency band.

Table 2: Upper frequency band coupled line filter parameters

Cline (N)	*l* (mm)	*w* (mm)	*s* (mm)
1	19.563	0.040	0.040
2	19.308	0.117	0.032
3	18.809	0.297	0.057
4	18.672	0.343	0.084
5	18.672	0.343	0.084
6	18.809	0.297	0.057
7	19.308	0.117	0.032
8	19.563	0.040	0.040

Fig. 6 (a) shows the schematic level simulation result of the 7th order coupled line bandpass filter with butterworth response for upper frequency band for which input reflection S11 is -12 Db, achieving the design requirements. On the other hand Fig. 6 (b) shows the simulation result of the forward transmission i.e. S21 of this filter which has a passband of 1.6 – 2.3 GHz being 30 % less than the LTE specification.





(a) (b)

Fig. 6. Schematic level simulation results of the 7th order coupled line bandpass filter with butterworth response for upper frequency band: (a) input reflection S11, and (b) forward transmission S21.

This result shows that this filter is not suitable because the passband is less than the design specification of the upper frequency band of LTE. It can be finally concluded from the coupled line filter design that it is highly unfeasible for being considered for the diplexer PCB fabrication because the PCB fabrication lab has a limitation on the minimum dimension that can be fabricated. For the achievement of the large bandwidth required for the LTE frequency bands a tight coupling between the coupled lines is required which cause the s to be very small [16]. The coupled line techniques like hairpin and zigzag are also not possible to be fabricated similarly.

B. STUB FILTER

The functionality of the stub filters can be understood by using a λ/4 bandpass filter prototype. The short-circuit stubs of λ/4 length are the shunt L-C equivalent of the lumped components bandpass filter where as the transmission lines of λ/4 length are the series LC equivalent of the lumped components bandpass filter.

Fig. 7 shows a 4th order bandpass filter using λ/4 transmission lines and λ/4 short-circuit stubs, the same filter can be converted to bandstop filter by replacing the short-circuit stubs with an open-circuit stubs. It is important to note that the λ/4 transmission line between the parallel connected short circuit stubs acts as a admittance inverter so that the impedance of this transmission line is equal to that of series connected L and C circuit at the transmission line which helps to realize an equivalent lumped components circuit of the bandpass filter [16].

The short-circuit stubs do the same task which the parallel LC circuits do in the lumped components filter i.e. acting as resonators to stop a particular frequency band. Further to that the transmission line also do the same task of series LC circuit in the lumped components filter i.e. allowing only a particular frequency band to pass to the load.

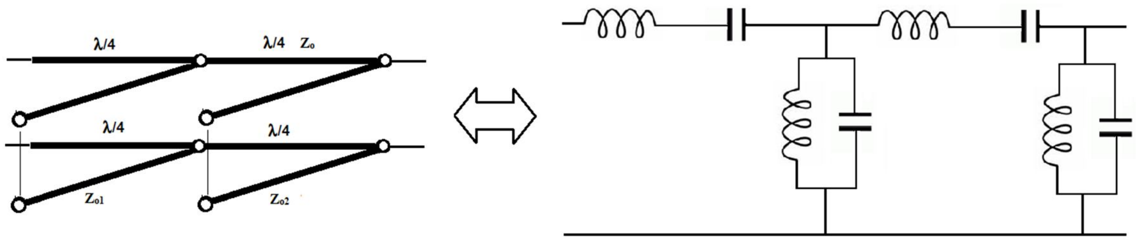


Fig. 7. A bandpass filter using quarter wave transmission lines and short-circuit stubs along with its lumped components equivalent circuit [14].

i. SIMULATION RESULTS

Finally stub filter was designed having all dimensions greater than 0.254 mm; it was investigated using the simulation results on schematic and layout level.

Similar to the lumped components filter and coupled line filter the stub filter design was initiated by designing a filter for lower frequency band which was 7th order bandpass filter with butterworth response. Fig. 7 shows the schematic diagram of the 7th order bandpass stub filter with butterworth response with transmission lines and double sided short-circuited stubs.

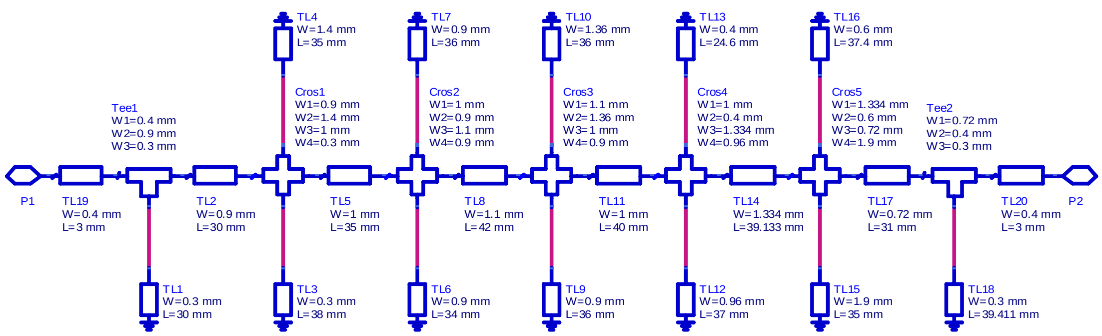
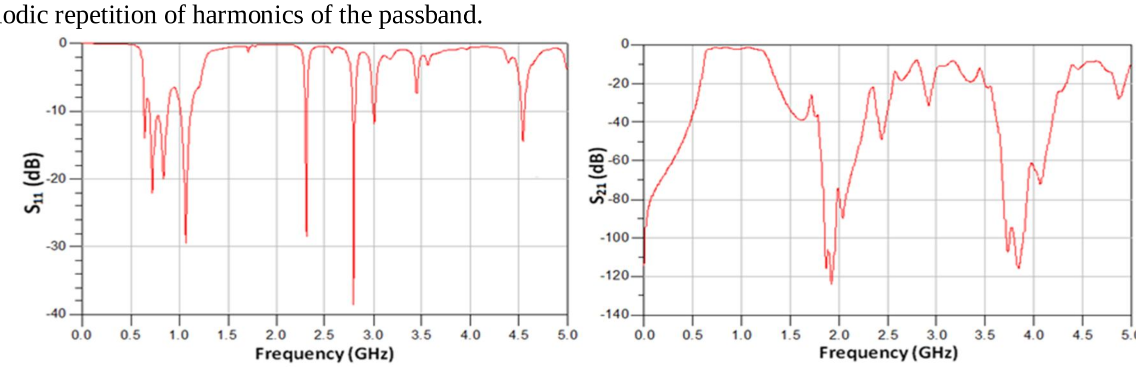


Fig. 8. Schematic of a 7th order bandpass stub filter with butterworth response for lower frequency band.

Fig. 9 (a) shows the simulation result of the schematic of a 7th order bandpass stub filter for lower frequency band with butterworth response having an input reflection S11 of -7 dB which is acceptable according to the design requirements. Fig. 8(b) shows the simulation result of the schematic of the 7th order bandpass stub filter for lower frequency band with butterworth response having the passband of 636 - 1200 MHz which is 115 % higher than the specified requirement for the lower frequency band of LTE. The reason for starting the design with higher order for the lower frequency bandpass stub filter was that bandwidth should be higher than specified requirement in order to compensate the losses during the integration of two filters for upper and lower frequency bands. The passband of this filter has bare minimum attenuation however the leakage is greater in the stop band near 3 GHz due to the periodic repetition of harmonics of the passband.



(a) (b)

Fig. 9. Simulation results of the schematic of the 7th order bandpass stub filter with butterworth response for lower frequency band: (a) input reflection S11, and (b) forward transmission S21.

The layout of the schematic of the 7th order bandpass stub filter with butterworth response is shown in fig. 10 which shows that the length of the filter is 230.5 mm and the width of the filter is 78.8 mm.

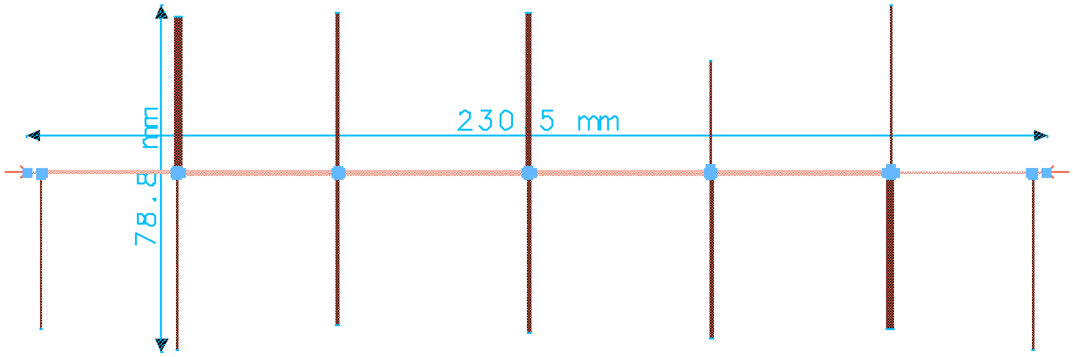


Fig. 10. Layout of a 7th order bandpass stub filter with butterworth response for lower frequency band.

Fig. 11(a) shows the simulation result of the layout of the lower frequency band 7th order bandpass stub filter with butterworth response showing input reflection S11 which is -7 dB, satisfying the design requirements. Fig. 11(b) shows the simulation result of the forward transmission S21 of this filter having a pass band of 635 – 1250 MHz which is 9 % increased from its schematic level simulation results due to the tuning of the filter on layout level. It can be additionally observed from this figure that attenuation is schematic level simulation results are in conformity with the layout level simulation results.

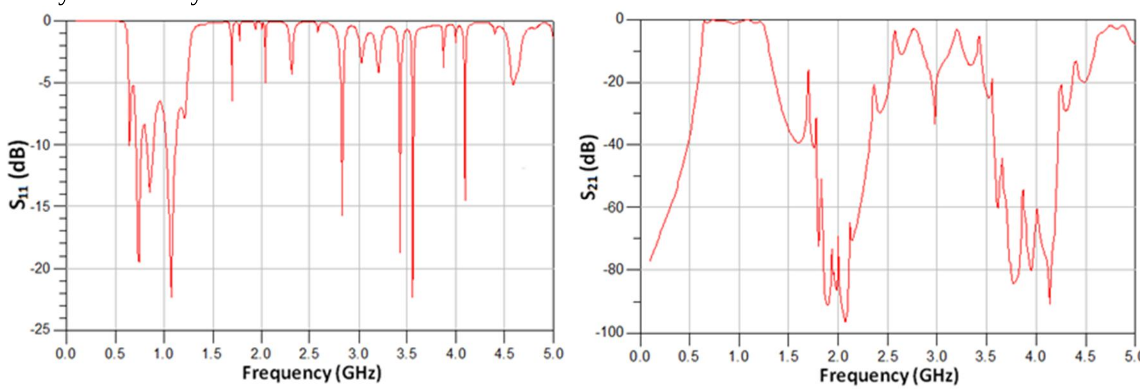


Fig. 11. Simulation results of the layout of 7th order bandpass stub filter with butterworth response for lower frequency band: (a) input reflection S11, and (b) forward transmission S21.

Fig. 12 shows the group delay on the layout level of the upper frequency band, 7th order bandpass stub filter with butterworth response. It is observed that the delay variation is roughly 0.6 ns and the maximum delay is as 9.5 ns.

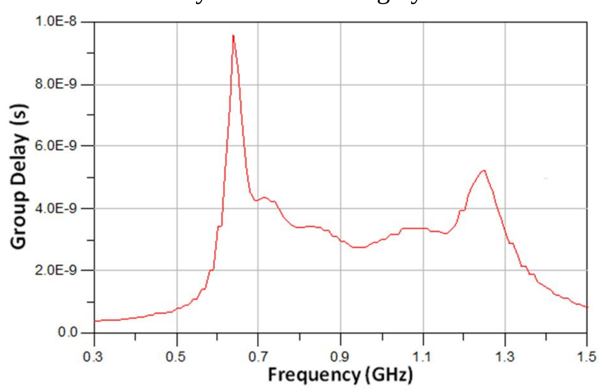


Fig. 12. Layout level group delay of the 7th order bandpass stub filter with butterworth response for lower frequency band.

Similar to the other filter designs the next step was to reduce the size of the filter so a 5th order bandpass stub filter whose schematic diagram is shown in fig. 13 was designed. It can be noticed from the schematic diagram that the number of distributed components i.e. transmission lines and stubs are reduced resulting in reduction of the filter size.

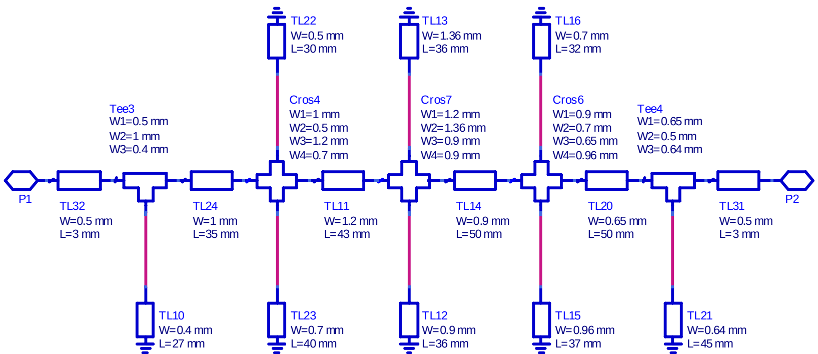
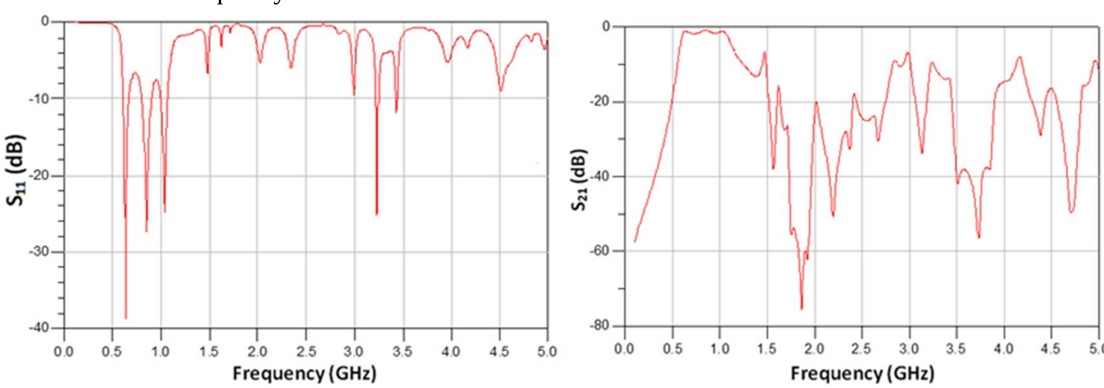


Fig. 13. Schematic of a 5th order bandpass stub filter with butterworth response for lower frequency band.

Fig. 14 (a) shows the simulation result of the schematic of 5th order bandpass stub filter for lower frequency band with butterworth response showing that the input reflection S11 is -7 dB which is in accordance with the design specification. Fig. 14(b) shows the simulation result of the schematic of the 5th order bandpass stub filter for lower frequency band with butterworth response. It shows that the attenuation in the pass band is slightly increased on the other hand the leakages in the stop band are suppressed as compared to the 7th order bandpass stub filter due to the tuning of filter parameters. The bandwidth of the passband i.e. 597- 1090 MHz has decreased 13 % as compared to the lower frequency band for 7th order stub filter.



(a) (b)

Fig. 14. Schematic level simulation results of a 5th order bandpass stub filter with butterworth response for lower frequency band: (a) input reflection S11, and (b) forward transmission S21.

The layout of the schematic of the 5th order bandpass stub filter with butterworth response is shown in fig. 15 which shows that the length of the filter is 188.1 mm and the width of the filter is 82.5 mm.

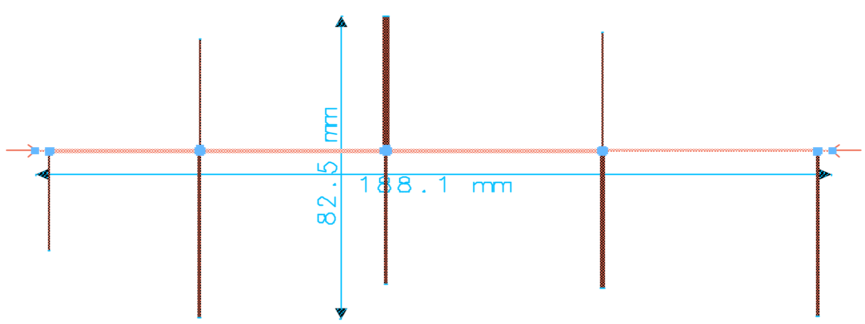


Fig. 15. Layout of a 5th order bandpass stub filter with butterworth response for lower frequency band.

Fig. 16 (a) shows the simulation result of the layout of the lower frequency band 5th order bandpass stub filter with butterworth response which has input reflection S11 of -7 dB, which is suitable according to the design requirement. On the other hand Fig. 16 (b) shows the simulation result of the forward transmission S21 of this filter having a passband of 586 – 1099 MHz which is 4 % increased from its schematic level simulation results as a result of fine tuning of the filter on layout level. It can also be observed from this figure that the attenuation is same for both schematic and layout simulations.

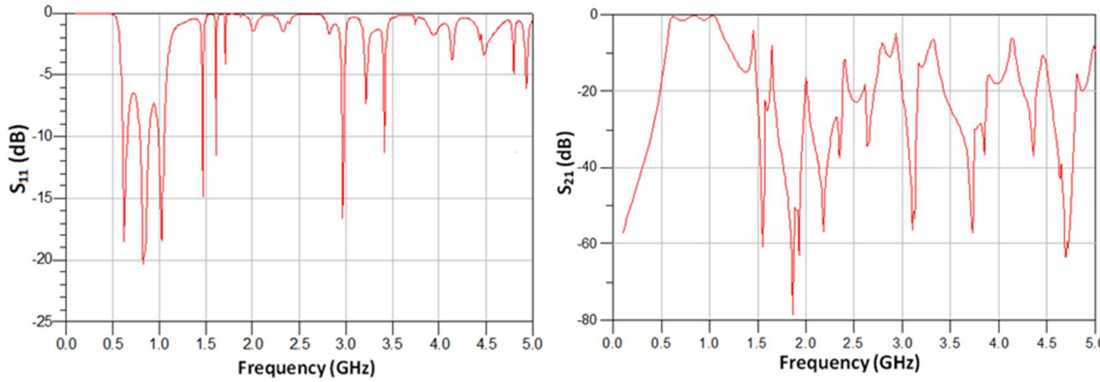


Fig. 16. Layout level simulation results of the 5th order bandpass stub filter with butterworth response for lower frequency band: (a) input reflection S11, and (b) forward transmission S21.

Fig. 17 shows the group delay on the layout level of the lower frequency band 5th order bandpass stub filter with butterworth response and it is observed that the delay variation is 0.6 ns and the maximum delay is 5 ns.

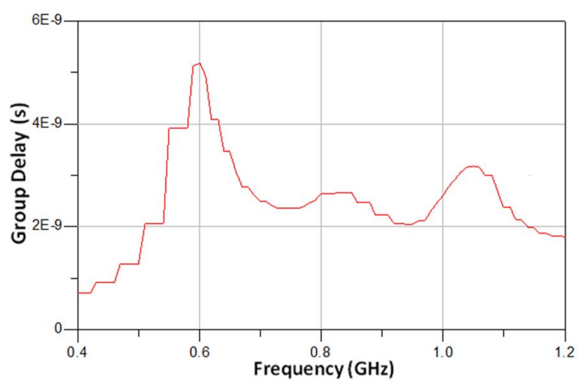


Fig. 17. Layout level group delay of the 5th order bandpass stub filter with butterworth response for lower frequency band.

Hence there are two lower frequency bandpass stub filters which can be used for diplexer design as they both have pros and cons which are summarized in the table 3.

Table 3: Comparison of 7th and 5th order bandpass stub filter for lower frequency band

Bandpass Stub Filter	Advantages	Disadvantages
7th order	higher bandwidth	large size
	less attenuation in pass band	more leakage in stop band
5th order	smaller Size	lower bandwidth
	less leakage in stop band	more attenuation in pass band

In the second phase of the stub filter design a bandpass filter was designed with butterworth response for upper frequency band see fig. 17 for the schematic diagram. It can be seen from this figure that the order is decreased to 4th and the size is also reduced.

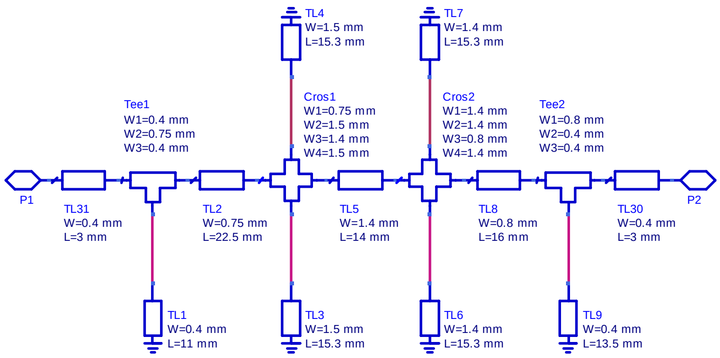
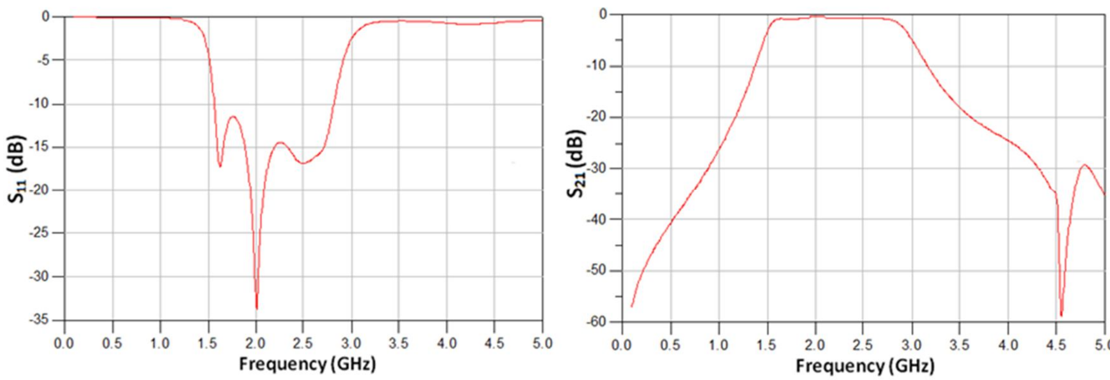


Fig. 18. Schematic of a 4th order bandpass stub filter with butterworth response for upper frequency band.

Fig. 19 (a) shows the simulation result of the schematic of 4th order bandpass stub filter for upper frequency band with butterworth response showing input reflection S11 is -12 dB meeting the design requisite and fig. 19 (b) shows the simulation result of the 4th order bandpass filter for upper frequency band with a passband of 1512 – 2931 MHz which is 43 % higher than the specified requirement of upper frequency band of LTE.



(a) (b)

Fig. 19. Schematic level simulation results of a 4th order bandpass stub filter with butterworth response for upper frequency band: (a) input reflection S11, and (b) forward transmission S21.

The layout of the schematic of the 4th order bandpass stub filter with butterworth response for upper frequency band is shown in fig. 20 which shows that the length of the filter is 62.2 mm and the width of the filter is 32.0 mm.

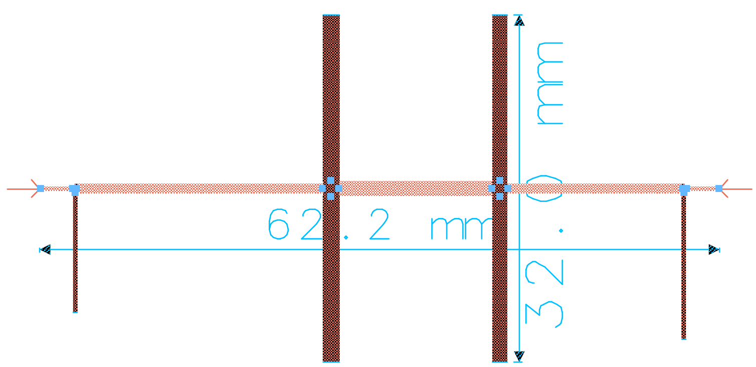
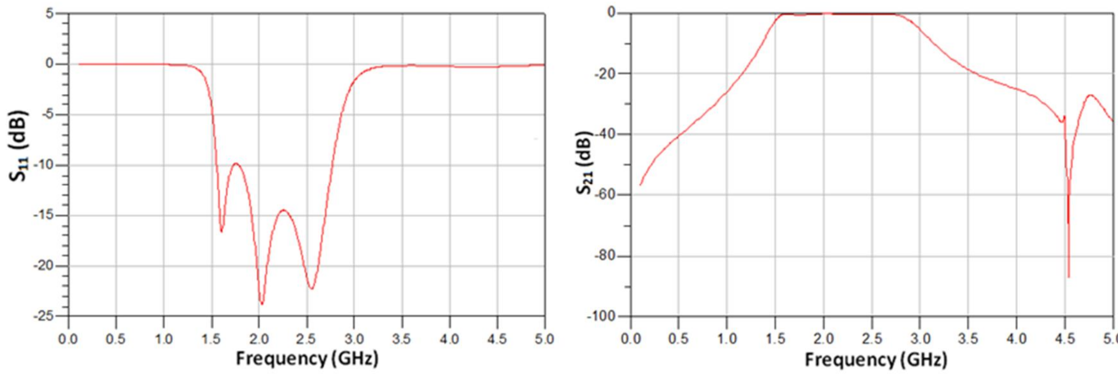


Fig. 20. Layout of a 4th order bandpass stub filter with butterworth response for upper frequency band.

Fig. 21 (a) shows the simulation result of the layout of the upper frequency band of 4th order bandpass stub filter with butterworth response showing input reflection S11 which is -10 dB, which is reasonable for design requirements. On the other hand fig. 21 (b) shows the simulation result of the forward transmission i.e. S21 of this filter which has a passband of 1495 – 2903 MHz and is 1 % decreased from its schematic level simulation results.

On the other hand the layout level simulation results of the 5th and the 7th order bandpass stub filters for lower frequency band were improved with better bandwidth due to tuning of the filter on layout level. Attenuations are also improved through tuning in the layout level simulations as compared to the schematic level simulations.



(a) (b)

Fig. 21. Simulation results of the layout of a 4th order bandpass stub filter with butterworth response for upper frequency band: (a) input reflection S11, and (b) forward transmission S21.

Fig. 22 shows the group delay on the layout level of the 4th order bandpass stub filter for upper frequency band and it is observed that within passband delay variation is 0.1 ns and maximum delay is less than 1.6 ns.

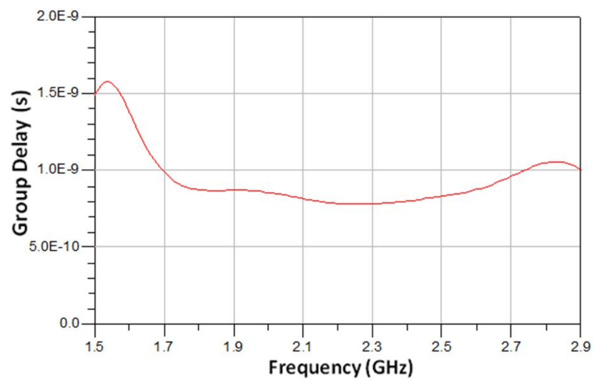


Fig. 22. Layout level group delay of the 4th order bandpass stub filter with butterworth response for upper frequency band.

V. DISTRIBUTED COMPONENTS DIPLEXER DESIGN

In this section two diplexer designs with two different combinations of the stub filters are analyzed. Firstly a 7th order bandpass stub filter for lower frequency passband which was integrated with a 4th order bandpass stub filter for upper frequency passband and analyzed.Secondly a 5th order bandpass stub filter for lower frequency passband which was integrated with a 4th order bandpass stub filter for upper frequency passband and analyzed.

A. STUB FILTER BASED DIPLEXER DESIGN

The stub filter based diplexer design requires two bandpass stub filters with butterworth response for upper and lower frequency passbands respectively. The passbands bandwidth for the designed filters is kept higher than the specification of the LTE in order to compensate the losses due to integration of the two filters for diplexer design as already mentioned in the lumped components diplexer design section. The next step is to connect the two filters together and to design a matching network.

The matching network for the stub filters was a transmission line in each of the filter branch passing the frequency band of the respective filter completely and providing infinite impedance to the frequency passband of the opposite branch filter. In the layout level the matching networks needs to be tuned up again to remove the leakages which are added.

i. SIMULATION RESULTS

Firstly the combination of a 7th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband along with transmission line based matching network in each of the filter branch was investigated for first diplexer design. This combination of filters and matching network served as a reference for the second diplexer design. The second diplexer consisted of the combination of a 5th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for the upper frequency passband along with transmission line based matching network in each of the filter branch.

Fig. 23 shows the schematic of the purely distributed first diplexer design with the combination of a 7th order bandpass stub filter and a 4th order bandpass stub filter and its transmission line matching network in each filter branch. The matching network for the two filter branches consisted of a transmission line in each branch which was matched to provide infinite impedance to the opposite branch frequency passbands.

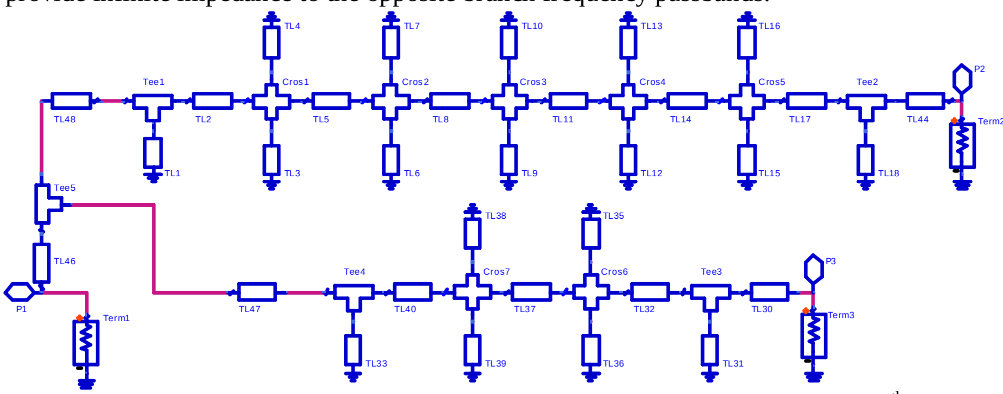
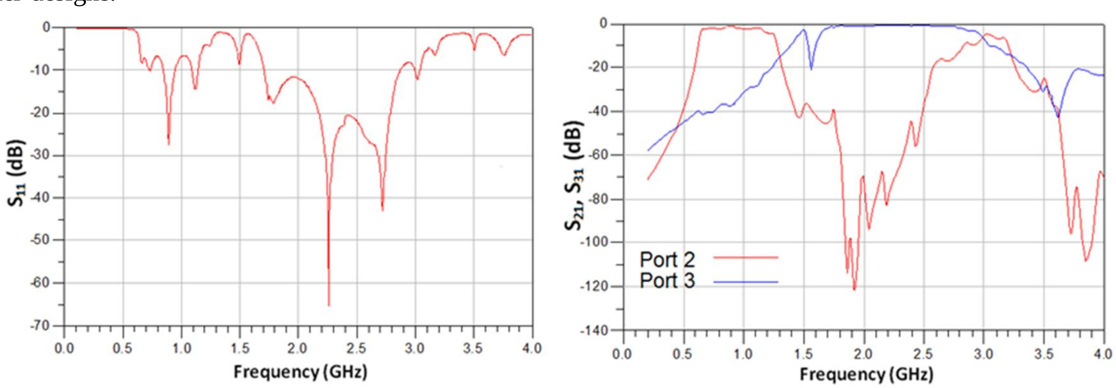


Figure 23: Schematic of a purely distributed first diplexer consisting of the combination of a 7^{th} order bandpass stub filter for lower frequency passband and a 4^{th} order bandpass stub filter for upper frequency passband with transmission line as a matching network.

Fig. 24 (a) shows the schematic level simulation result of input reflection S11 for the purely distributed first diplexer design and it is observed to be less than -8 dB for both upper and lower frequency passbands. Fig. 24 (b) shows the schematic level simulation result of the forward transmission of the purely distributed first diplexer design which has the lower frequency passband of 652 – 1162 MHz and an upper frequency passband of 1671 – 2845 MHz. If these results are compared to the LTE upper and lower frequency passbands there is a 95 % increase in the lower frequency passband and 19 % increase in the upper frequency passband. The bandwidth was increased in both of the bands to give margin for losses occurring during fabrication of the first diplexer design similar to the previous diplexer designs.



(a) (b)

Figure 24: Simulation results of a purely distributed first diplexer consisting of the combination of a 7^{th} order bandpass stub filter for lower frequency passband and a 4^{th} order bandpass stub filter for upper frequency passband with transmission line as a matching network: (a) input reflection S11, and (b) forward transmission.

The layout of the schematic of the purely distributed first diplexer design is shown in figure 24 which shows that the length of the board is 254.6 mm and width of the board is 135.6 mm

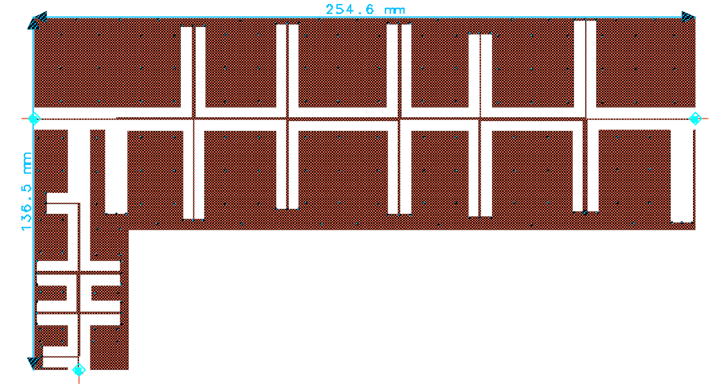
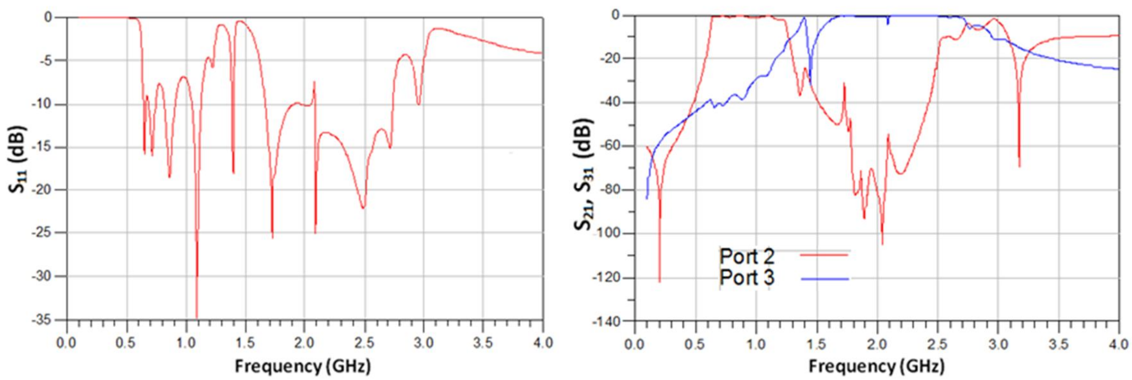


Figure 25: Layout of a purely distributed first diplexer consisting of the combination of a 7th order bandpass stub filter for lower frequency passband and 4th order bandpass stub filter for upper frequency passband with transmission line as a matching network.

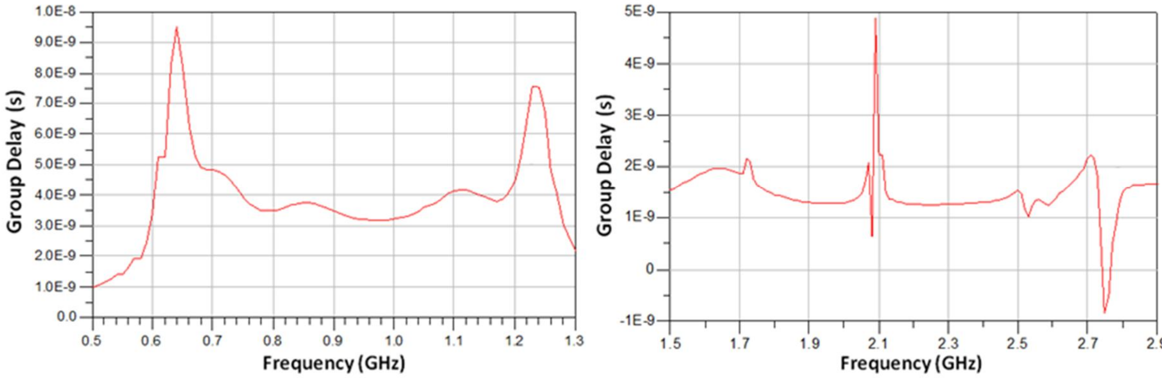
Figure 26 (a) shows the simulation result of the layout of the purely distributed components first diplexer consisting of the combination of a 7th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for the upper frequency passband. It can be observed from the figure that input reflection S11 for both upper and lower frequency passbands are less than -7 dB. Whereas figure 26 (b) shows the layout level simulation result of the forward transmission of the first diplexer and it can be observed from the figure that it has a lower frequency passband of 632 - 1237 MHz and an upper frequency passband of 1598 – 2726 MHz which is slightly deviated as compared to the schematic level. Leakages are observed in the upper frequency passband at 1.4 GHz and 2 GHz due to losses accompanied in the substrate.



(a) (b)

Figure 26. Simulation results of the layout of a purely distributed first diplexer consisting of the combination of a 7th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission lines as matching network: (a) input reflection S11, and (b) forward transmission.

Figure 27 shows the group delay on the layout level of the purely distributed first diplexer design. Fig. 27 (a) shows the delay for lower frequency passband in which the delay variation is nearly 1 ns and the maximum delay is 9.5 ns .Whereas fig. 27 (b) shows the delay for upper frequency passband in which the maximum delay is 2.2 ns and the inband delay variation is approximately 1 ns.



(a) (b)

Figure 27. Group delay of the layout of a purely distributed first diplexer consisting of the combination of a 7th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission lines as matching network: (a) group delay for lower frequency passband, and (b) group delay for upper frequency passband.

Fig. 28 shows the isolation on the layout level of a purely distributed first diplexer. This figure shows the isolation between port 3-2 and it has a minimum value of 20 dB.

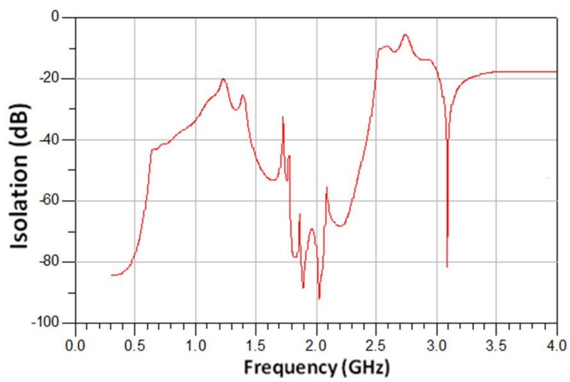


Figure 28. Isolation of the layout of a purely distributed first diplexer consisting of the combination of a 7th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission lines as matching network between ports 3-2.

The second diplexer design which consisted of the combination of a 5th order bandpass stub filter designed for the lower frequency passband and a 4th order bandpass stub filter designed for the upper frequency passband had the same matching network as the one used for the first diplexer design.

Fig. 29 shows the schematic of the the purely distributed second diplexer design with the combination of a 5th order bandpass stub filter and a 4th order bandpass stub filter along with their respective matching network for upper and lower frequency passbands. It can be observed from the schematics that the number of distributed components have decreased as compared to the first diplexer design.

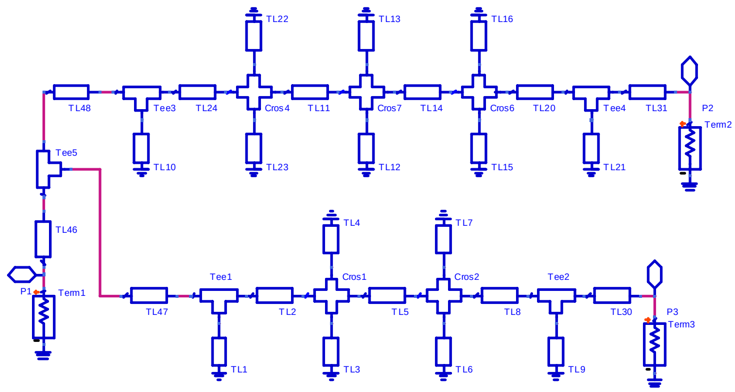
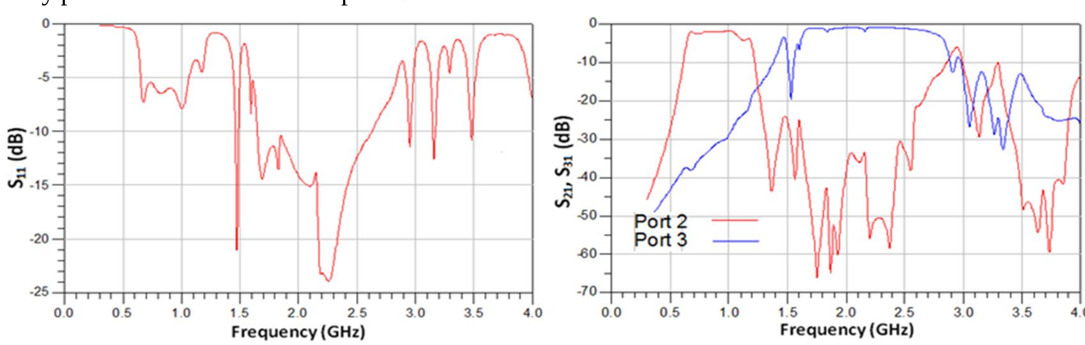


Figure 29. Schematic of a purely distributed second diplexer consisting of the combination of a 5th order bandpass stub filter for low frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission line as a matching network.

Figure 30(a) shows the schematic level simulation result of input reflection S11 for the purely distributed second diplexer design for both upper and lower frequency passbands and they are observed to be less than -6 dB. The schematic level simulation result of the forward transmission is shown in figure 30(b) and it shows that there is a 57% increase i.e. 654 – 1066 MHz of the bandwidth for the lower frequency passband and in the upper frequency passband there is a 17 % increase i.e. 1627 – 2790 MHz compared with LTE frequency passbands. From this figure it can also be seen that the attenuation in the lower frequency passband has slightly increased and also the upper frequency passband has some minor peaks.



(a) (b)

Figure 31. Simulation results of a purely distributed second diplexer consisting of the combination of a 5th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission line as a matching network: (a) input reflection S11, and (b) forward transmission.

Figure 31 shows the layout of the purely distributed second diplexer and it shows that the length of the board is 178.3 mm and the width of the board is 129.4 mm.

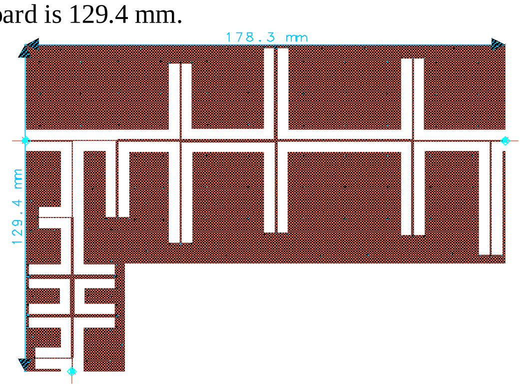
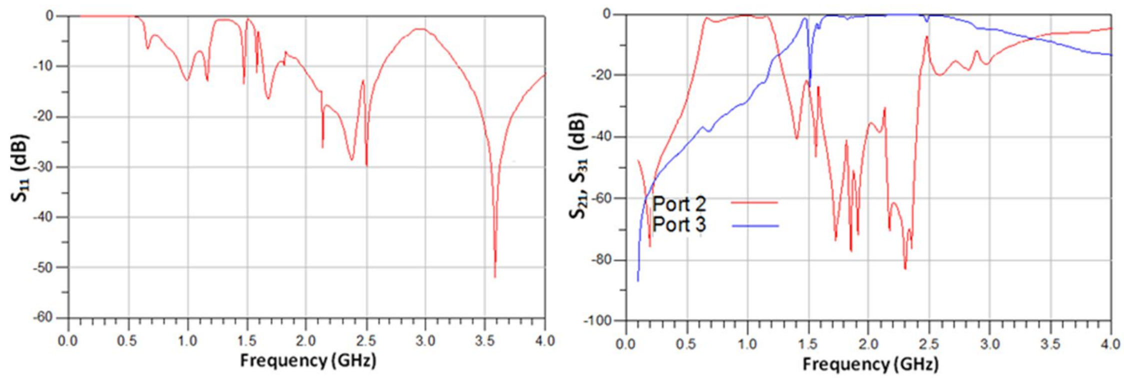


Figure 31. Layout of a purely distributed second diplexer consisting of the combination of a 5th order bandpass stub filter for low frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission line as a matching network.

Figure 32 (a) shows the simulation result of the layout of the purely distributed components second diplexer consisting of the combination of a 5th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for the upper frequency passband. It can be observed from the figure that the input reflection S11 for both lower and upper frequency passbands are less than -6 dB. On the other hand Fig. 32 (b) shows the forward transmission of this diplexer and it can be observed from the figure that the diplexer has a lower frequency passband of 642 – 1198 MHz which is 35 % increased as compared to the schematic level simulation result of this diplexer. On the other hand the upper frequency passband is 1598 - 2838 MHz which is also 7 % increased from the schematic level. The reason for the increase in bandwidth was that the layout level simulations were optimized in order to get better results. The attenuation in both bands had also decreased due to the tuning however still there was leakage at 1.47 GHz near the upper frequency passband.



(a) (b)

Figure 32. Groupdelay of the layout of a purely distributed second diplexer consisting of the combination of a 5th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission lines as a matching network: (a) for lower frequency passband, and (b) for upper frequency passband.

Figure 33 shows the isolation on the layout level of a purely distributed second diplexer between ports 3-2 and the minimum isolation is 22 dB.

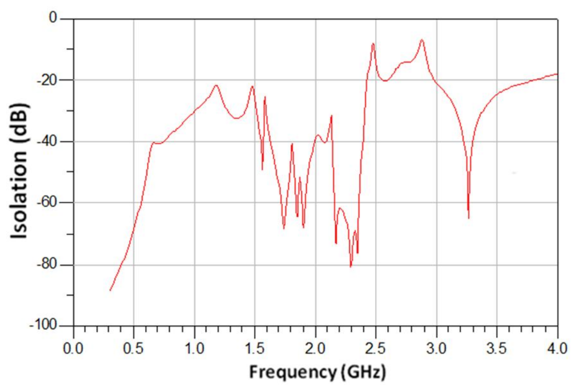


Figure 33. Isolation of the layout of a purely distributed second diplexer consisting of the combination of a 5th order bandpass stub filter for lower frequency passband and a 4th order bandpass stub filter for upper frequency passband with transmission lines as matching network between ports 3-2.

VI. RESULTS AND DISCUSSION

In this section the measured results for forward transmission (S21, S31) of the selected diplexer are discussed. Fig. 34 shows the photo of the implementation of the purely distributed components first prototype diplexer. It can be seen from the figure that the solder was used to compensate the vias which were not copper platted due to problem faced during electrolysis process as the electrodes were faulty in the ITN PCB laboratory's electrolysis chamber , Linkoping University , Sweden, but as the vias dimensions were so small the solder was also not able to connect the ground planes.

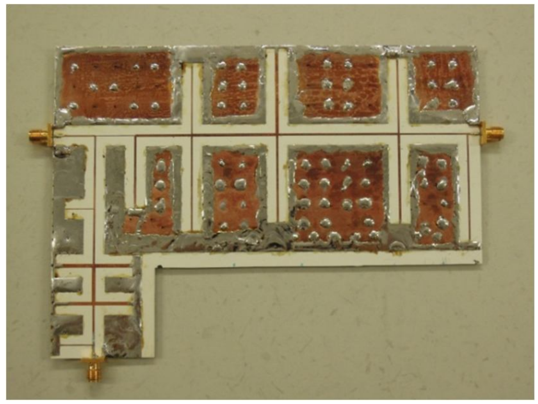


Fig. 34. Photo of the implementation of the prototype of the selected distributed components diplexer.

Fig. 35 shows the measured and simulated results of the forward transmission of the purely distributed first prototype diplexer. It can be observed that the lower frequency passband of measured result is quite similar to the simulated result. On the other hand for the upper frequency passband the leakages and attenuations have increased severely and the bandwidth has also decreased to a large extent in the measured results. The reason for this is that at higher frequency range the transmission lines and stubs are subjected to skin effect as the high frequency signals used for measurements have high magnetic field and are moved to the outer perimeter of the copper trace leaving hollow copper in the middle of the trace. The high frequency signal therefore experiences large resistance as the total area of the copper trace is reduced. Secondly the leakages were also caused due to inductance in the PCB which was created due to improper copper plating in the vias which made the connection with the ground on the opposite side of the PCB to be bad due to faulty electrodes in the electroplating equipment in the ITN PCB laboratory , Linkoping University , Sweden.

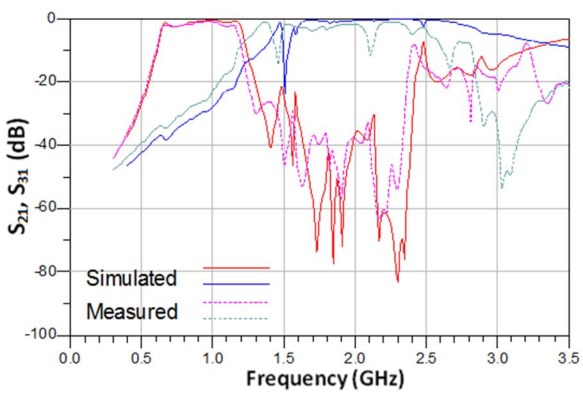


Fig. 35. Measured and simulated results of the forward transmission of a purely distributed components first prototype diplexer.

VII. CONCLUSION AND FUTURE WORK

In this paper , the objective is to investigate the distributed components filter designs for achieving reduction of the size of diplexer as well as to achieve the LTE frequency passbands 690 – 960 MHz and 1710 – 2700 MHz. It was concluded that the 5th order stubfilter for lower LTE frequency band integrated using transmission line matching technique with the 4th order stubfilter for upper LTE frequency band had measured results are in agreement with the simulated results. The leakages increased in the upped LTE frequency band due to the poor electroplating of the vias and the skin effect caused at high frequency in the conductor. This design had small dimensions i.e. length is 254.6mm and width is 135.6mm however it can be further reduced using meander technique.

The lumped components filter can also be used for lower LTE frequency band instead of distributed components filter for further reduction of the diplexer size.

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