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Design of 250-500 MHz Switched filter bank for GMRT using Metamaterial ZOR Techniques

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Index

1.0 Introduction

Giant Meter wave Radio Telescope (GMRT) has been designed to operate at six frequency bands centered at 50 MHz, 150 MHz, 235 MHz, 327 MHz, 610 MHz and L-Band extending from 1000 MHz to 1450 MHz. L-band is split into four sub-bands centered at 1060 MHz, 1170 MHz, 1280 MHz and 1390 MHz, each with bandwidth of 120 MHz . The 150 MHz, 235 MHz and 327 MHz bands have about 40 MHz bandwidth and 610 MHz band has about 60 MHz bandwidth. Lower frequency bands from 150 MHz to 610 MHz have dual circular polarization channels (Right Hand Circular and Left Hand Circular) which have been conveniently named as CH1 and CH2 respectively.

This report attempts to describe design of switch filter bank for upgraded 325 MHz (250-500 MHz) front end system using MeTaMaterial (MTM) Zeroth Order Resonator (ZOR) technique. The objective of using MTM-ZOR technique is to reduce the filter size is compare to the conventional design. It is observed that using MTM-ZOR technique the filter size is reduced by a factor of six times compare to couple line design and four times compare to hairpin design.

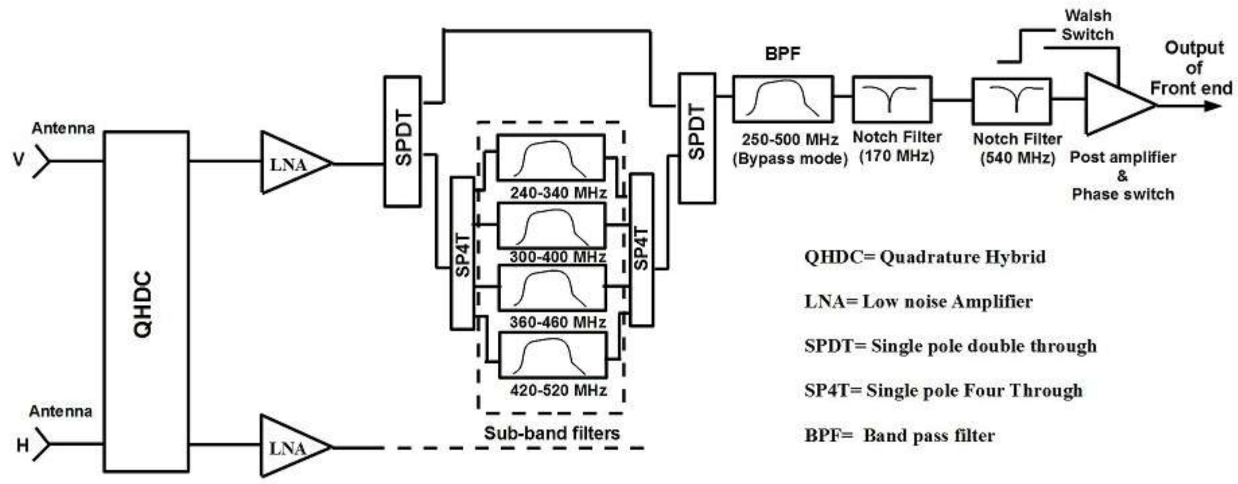


Fig.1. Upgraded Front End System -325 MHz-Band

Fig.1. shows block diagram of upgrade 250-500 MHz front end system with switch filter bank. The switch filter bank consists of four sub bands, 240-340 MHz, 300-400 MHz, 360-460 MHz, and 420-520 MHz along with 250-500 MHz main band pass filter. Each sub band is 100 MHz bandwidth (6 dB points). The document covers fundamental of various type of filters, detail

design of MTM-ZOR based band pass filter and its compression with the conventional microstrip filters. The design is done using ADS-2012 software which work on Method of moments. Rogers RT droid board RT 6010 is used for this design.

2.0 Fundamentals of Filter

Filters are networks that process signals in a frequency-dependent manner. The basic concept of a filter can be explained by examining the frequency dependent nature of the impedance of capacitors and inductors. Consider a voltage divider where the shunt leg is reactive impedance. As the frequency is changed, the value of the reactive impedance changes, and the voltage divider ratio changes. This mechanism yields the frequency dependent change in the input/output transfer function that is defined as the frequency response.

An ideal filter will have an amplitude response that is unity (or at a fixed gain) for the frequencies of interest (called the *pass band*) and zero everywhere else (called the *stop band*). The frequency at which the response changes from passband to stopband is referred to as the *cutoff frequency*. The functional complement to the low-pass filter is the high-pass filter. Here, the low frequencies are in the stop-band, and the high frequencies are in the pass band. Figure 1 shows the idealized response of all conventional filters.

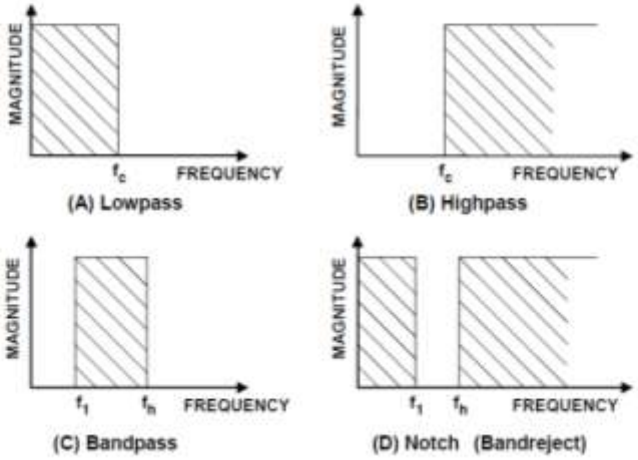


Fig.1. Idealized Filter Responses

If a high-pass filter and a low-pass filter are cascaded, a *band pass* filter is created. The band pass filter passes a band of frequencies between a lower cutoff frequency, $f\,l$, and an upper cutoff frequency, f_h. Frequencies below f_l and above f_h are in the stop band. An idealized band pass filter is shown in Fig.1(C).A complement to the band pass filter is the *band-reject*, or *notch* filter. Here, the pass bands include frequencies below f_l and above f_h. The band from f_l to f_h is in the stop band. Fig.1(D) shows a notch response. The idealized filters defined above, unfortunately, cannot be easily built. The transition from pass band to stop band will not be instantaneous, but instead there will be a transition region. Stop band attenuation will not be infinite. The five parameters of a practical filter are defined in Fig.2, opposite. The *cutoff frequency* (F_c) is the frequency at which the filter response leaves the error band (or the −3 dB point for a Butterworth response filter). The *stop band frequency* (F_s) is the frequency at which the minimum attenuation in the stopband is reached. The *pass band ripple* (A_{max}) is the variation (error band) in the pass band response. The *minimum pass band attenuation* (A_{min}) defines the minimum signal attenuation within the stop band. The steepness of the filter is defined as the *order* (M) of the filter. M is also the number of poles in the transfer function. A pole is a root of the denominator of the transfer function. Conversely, a zero is a root of the numerator of the transfer function

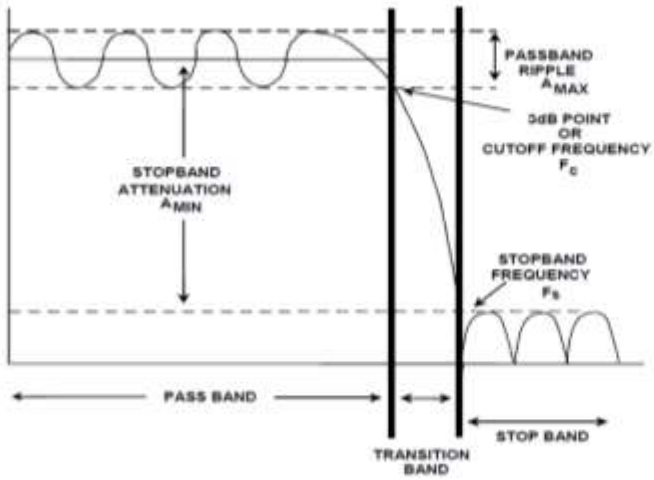
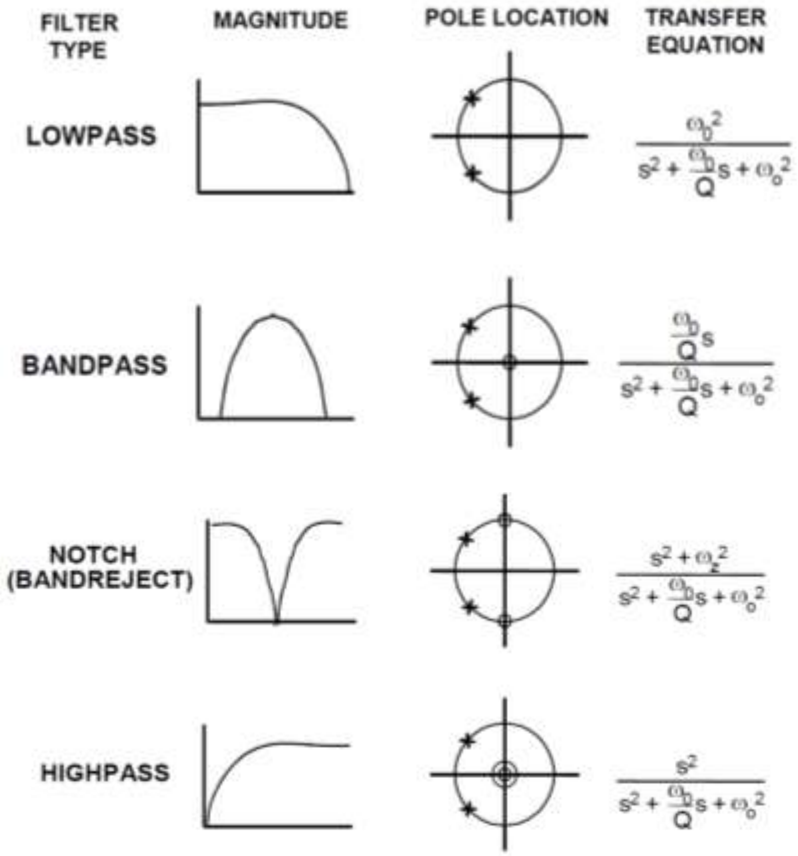


Fig.2: Key Filter Parameters

Note that not all filters will have all these features. For instance, all-pole configurations (i.e. no zeros in the transfer function) will not have ripple in the stop band. Butterworth and Bessel filters are examples of all-pole filters with no ripple in the pass band. Typically, one or more of the above parameters will be variable. For instance, if you were to design an antialiasing filter for an ADC, you will know the cutoff frequency (the maximum frequency that you want to pass), the stop band frequency, (which will generally be the Nyquist frequency (= ½ the sample rate)) and the minimum attenuation required (which will be set by the resolution or dynamic range of the system). You can then go to a chart or computer program to determine the other parameters, such as filter order, F0, and Q, which determines the peaking of the section, for the various sections and/or component values. It should also be pointed out that the filter will affect the phase of a signal, as well as the amplitude. For example, a single-pole section will have a 90° phase shift at the crossover frequency. A pole pair will have a 180° phase shift at the crossover frequency. The Q of the filter will determine the rate of change of the phase. Fig.3 refereed filter response(frequency domain) and corresponding there transfer function.



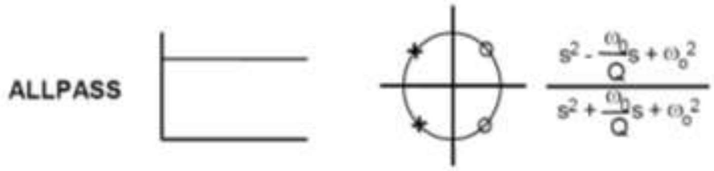


Fig.3. Standard Second-order Filter Responses and there corresponding transfer functions.

2.1 Standerd filter responses

There are many transfer functions that may satisfy the attenuation and/or phase requirements of a particular filter. The one that you choose will depend on the particular system. The importance of the frequency domain response versus the time domain response must be determined.

Butterworth

The Butterworth filter is the best compromise between attenuation and phase response. It has no ripple in the pass band or the stop band, and because of this is sometimes called a maximally flat filter. The Butterworth filter achieves its flatness at the expense of a relatively wide transition region from pass band to stop band, with average transient characteristics.

Chebyshev

The Chebyshev (or Chevyshev, Tschebychev, Tschebyscheff or Tchevysheff, depending on how you translate from Russian) filter has a smaller transition region than the same order Butterworth filter, at the expense of ripples in its pass band. This filter gets its name because the Chebyshev filter minimizes the height of the maximum ripple, which is the Chebyshev criterion.

Bessel

Butterworth filters have fairly good amplitude and transient behavior. The Chebyshev filters improve on the amplitude response at the expense of transient behavior. The Bessel filter is optimized to obtain better transient response due to a linear phase (i.e.constant delay) in the passband. This means that there will be relatively poorer frequency response (less amplitude discrimination).

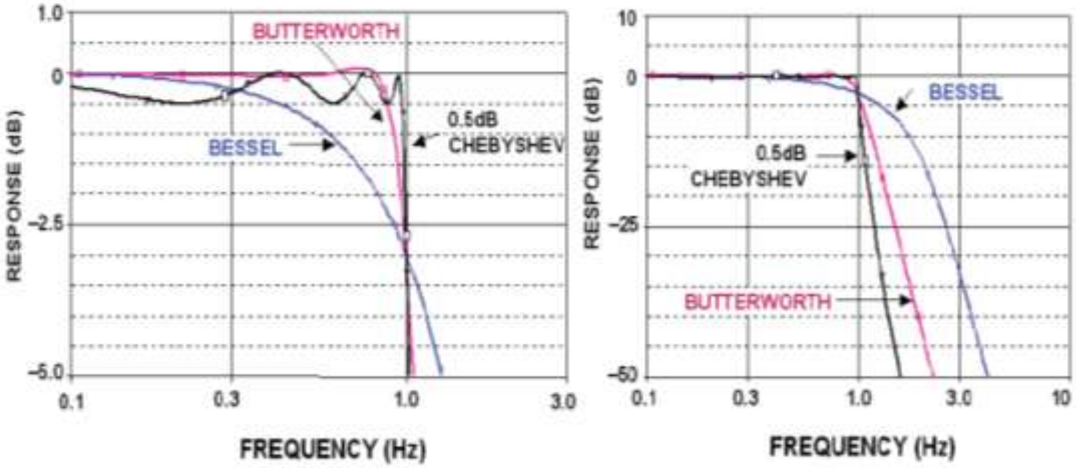


Fig.4. Comparison of Amplitude Response of Bessel, Butterworth, and Chebyshev Filters

2.2 Realization of Band Pass Filter using Lumped components

A Band Pass Filter allows a specific frequency range to pass, while blocking lower and higher frequencies. It allows frequencies between two cut-off frequencies while attenuating frequencies outside the cut-off frequencies.

A good application of a band pass filter is in Audio Signal Processing, where a specific range of frequencies of sound are required while eliminating the rest. Another application is in the selection of a specific signal from a range of signals in communication systems.

A band pass filter may be constructed by cascading a High Pass RL filter with a roll-off frequency f_L and a Low Pass RC filter with a roll-off frequency f_H , such that

$$f_L<f_H \tag{1}$$

The Lower cut-off frequency is given as: $\dfrac{R}{2\pi L}$ (2)

The higher cut-off frequency is given as: $\dfrac{1}{2\pi RC}$ (3)

The Band Width of frequencies passed is given by:$BW=f_H-f_L$ (4)

It is the graph of magnitude of the output voltage of the filter is a function of frequency. It is generally used to characterize the range of frequencies in which the filter is designed to operate within. Fig.5 shows a typical frequency response of a Band Pass filter.

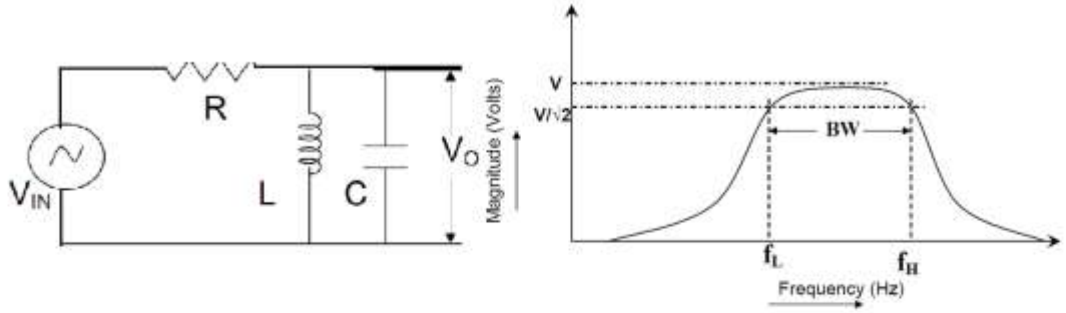


Fig.5. (a) Circuit diagram for a Band pass Filter. (b) Frequency response of Band pass filter.

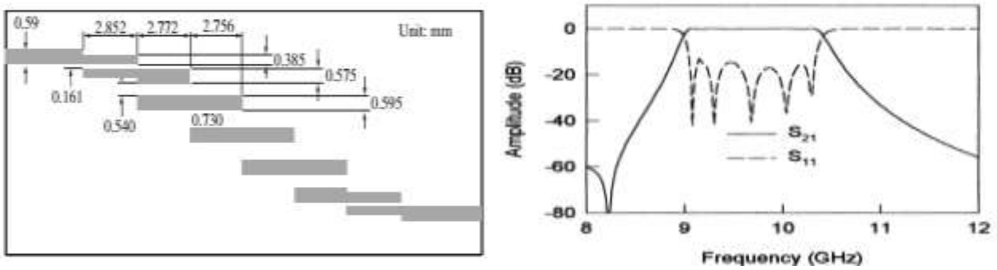
Realization of bandpass filter using lumped components in low frequency is easy compare to microstrip (distributed circuits), due to its frequency depended characteristics. But in the lumped components you have to tune your filter every time before it use, instead of using microstrip there is no need of tuning. If any microstrip circuit whose dimension is invariant of wavelength such circuits can be used in our application where the operation frequency is very low. Before going such type of circuits we first give some brief idea on microstrip based band pass filter design.

3.0 Microstrip Band Pass Filter (BPF) design

Microstrip configuration is a conducting strip in a dielectric host. In microstrip configuration partially it is in host dielectric and partially in air that’s why the wave it’s propagated it is called quasi TEM. The band pass filter using microstrip can be realized in many way but due to scope of limitation we will discuss three filter schemes. Those are coupled line filter, hairpin filter, open loop filter. The transformation of lumped components to distributed circuits is discussed in Appendix-2.

3.1 Coupled Line filter

The general structure of parallel coupled filter (or edge coupled) microstrip filter is used half wavelength of a resonator. The adjacent positions are half wavelength separation. This parallel arrangement gives relatively large coupling for a given spacing between the resonators, and thus structures is used for wide band filter purpose. The design of filter and its frequency response is given Fig.6.



(a) (b)

Fig.6 (a) Layout of a five-pole microstrip bandpass filter Coupled line design. (*b*) Frequency responses of the filter obtained by full-wave EM simulations.

3.2 Hairpin filter

Hairpin filter is a compact structure, conceptually by folding the resonator of the parallel coupled resonator into U shape. However the fold of resonator it is necessary to take into account the resonator length to reduce the coupling effects. The design of filter and its frequency response is given Fig.7.

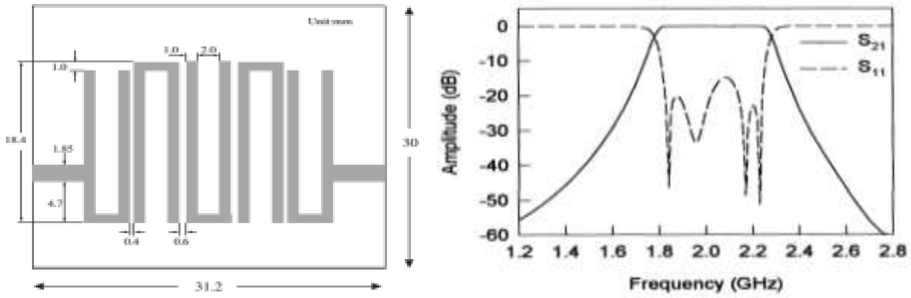
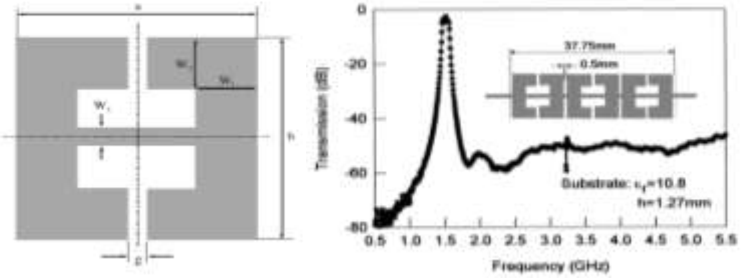


Fig.7 (a) Layout of a five-pole, hairpin-line microstrip bandpass filter. (*b*) Full-wave simulated performance of the filter.

3.3 Open Loop filter

Fig 8 illustrates a symmetrical microstrip slow-wave resonator, which is composed of a microstrip line with both ends loaded with a pair of folded open stubs. Assume that the open stubs are shorter than a quarter-wavelength at the frequency considered, and the loading is capacitive.



(a) (b)

Fig.8. (a) Microstrip slow-wave resonator. (*b*) Layout and measured frequency response of end-coupled microstrip slow-wave resonator bandpass filter.

3.4 Interdigital Bandpass Filters

This type of microstrip bandpass filter is compact, but requires use of grounding microstrip resonators, which is usually accomplished with via holes. However, because the resonators are quarter-wavelength long using the grounding, the second passband of filter is centered at about three times the mid band frequency of the desired first passband, and there is no possibility of any spurious response in between. For the filters with parallel-coupled, half-wavelength resonators described in the previous section, a spurious passband at around twice the mid band frequency is almost always excited (Fig.9).

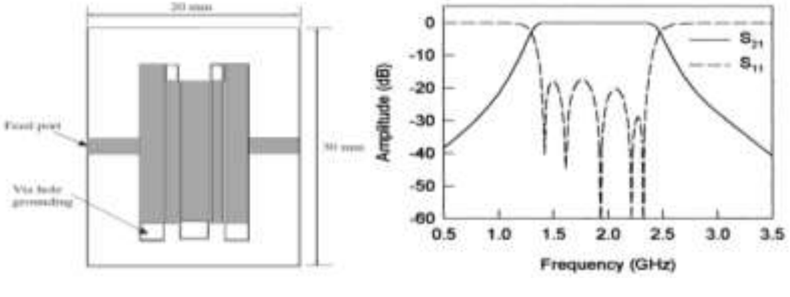


Fig.9. (*a*) Layout of a five-pole, microstrip interdigital bandpass filter using asymmetrical coupled lines. (*b*) Full-wave EM simulated performance of the filter.

Metamaterial (MTM) is an artificial composite material where we can change its electromagnetic properties. The equivalent circuit approach of MTM was developed by Caloz and Itoh and Eleftheriades and this approach has led to the concept of Composite Right and Left Handed (CRLH) materials, which fully takes into account the parasitic Right-Handed (RH) effects which is unavoidable in a practical application. The Zeroth Order Resonator (ZOR) has the mode number zero and its resonator length is invariant of its wavelength, Sanada et al. first proposed MTM-ZOR and realized it in microstrip configuration. Using MTM-ZOR technique several researchers have designed Band Pass Filters (BPF) in different frequency bands.

4.0 MTM-ZOR Band pass filter design

MTM circuit is a series and shunt capacitor (C_L) and inductor (L_L) where the propagation constant (β) is negative in a specific frequency band. This type of transmission line is called `Periodically Left Handed Transmission line' (PLTL). Making a practical PLTL is not possible due to unavoidable parasitic right handed effects.

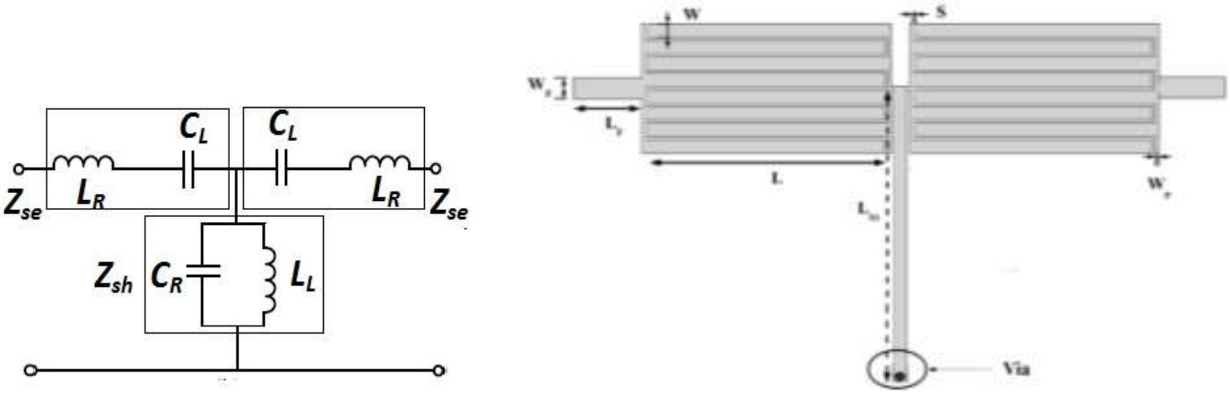


Fig.10. (a) Unit Cell model of MTM transmission line (TL). (b) Equivalent microstrip model MTM-TL.

The unit cell model of MTM-TL and its equivalent microstrip model are given Fig.10. The calculations of the unit cell shunt inductor L_L (H-m) and series capacitor C_L (F-m). For making the unit cell response at 500 MHz (Center frequency), values are 0.6 nH, and 4 pF. From the above design, the unit-cell parameters are; W=1mm, l_d=10mm, g=0.3mm, W_stub=0.7mm, l_stub=21 mm, via=0.3mm (diameter), inter digital filter gap length=4.8mm, and the number of interdigital lines, n =8.

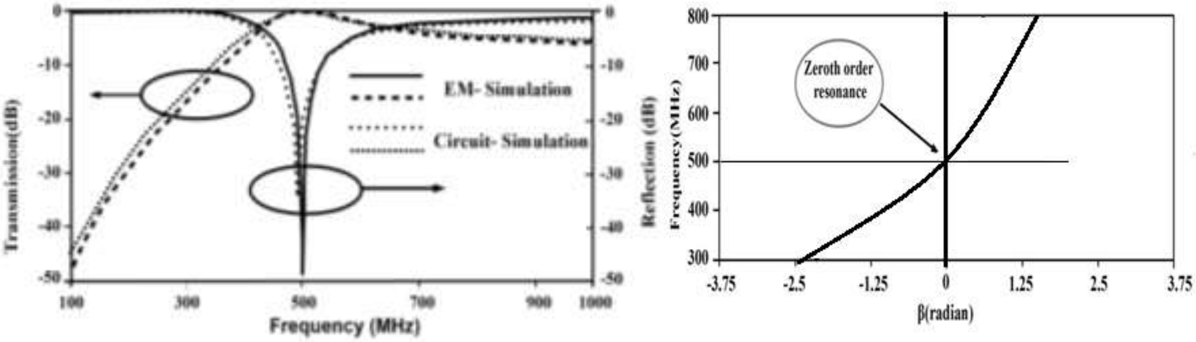


Fig.11. Scattering parameter and dispersion curve of CRLH unit cell.

Using these specifications we designed a microstrip based unit cell (MTM-ZOR). Its unit cell scattering parameter and dispersion (ω / β) curves are given in Fig.11.

After getting the response of a single unit cell we designed a five pole filter for 420-520 MHz to achieve a better roll-off. For making a BPF the individual unit of MTM-ZOR was made after which the units are connected to the Inter Ring Coupler (IRC). IRC forms the bridge between each resonator. The schematic figure of resonators connected with IRC is given Fig.12.

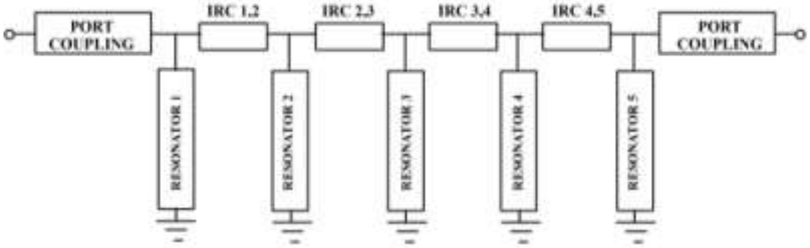
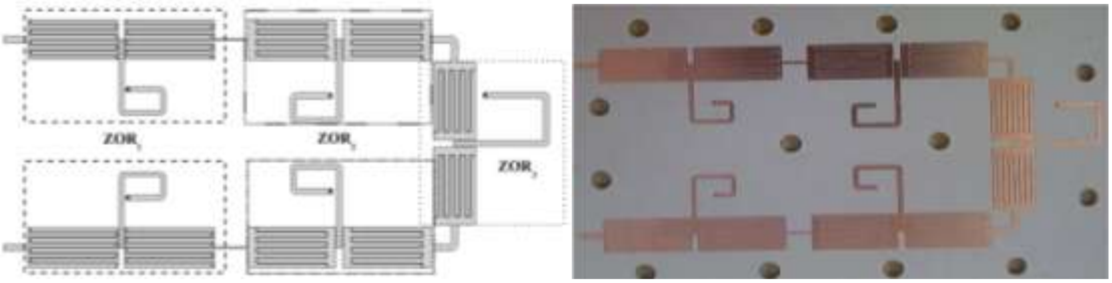


Fig.12. Inter ring coupling of (two) MTM-ZOR unit cells.

The EM simulated structure and its fabricated design are given Fig.13 (a) and (b). The technical specifications are given Table-1. For fabricating our prototype we used RT Duroid 6010, height of substrate being 1.27 mm and metal thickness, 35 µm.

Table: 1

Item	**Specification**
Central frequency(f_0)	470 MHz
Bandwidth (6dB)	100 MHz
Insertion loss	< 3 dB
Return loss in the pass band	>=10 dB
Sharp skirt(Attenuation at f_{ue}+30 MHz)	>=20dB



(a) (b)

Fig.13. Compact five poles CRLH-ZOR filter (a) EM-simulation (b) Fabricated Design.

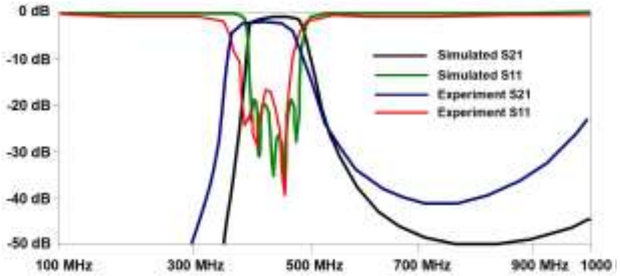


Fig.143. Simulated and Experimental results of the LHM-ZOR based BPF (S_{11}, S_{21})

The dimensions of this LHM-ZOR filter 5.21cm x 2. 9cm. Fig.14 it's observed that our simulation results are not well matched to the experimental measurement due probably to variations in the substrate dielectric constant and its height being not uniform throughout the board. Further there may also be fabrication errors. Before designing a better in band response we examined how the higher frequency skirt and the band width depend on each other.

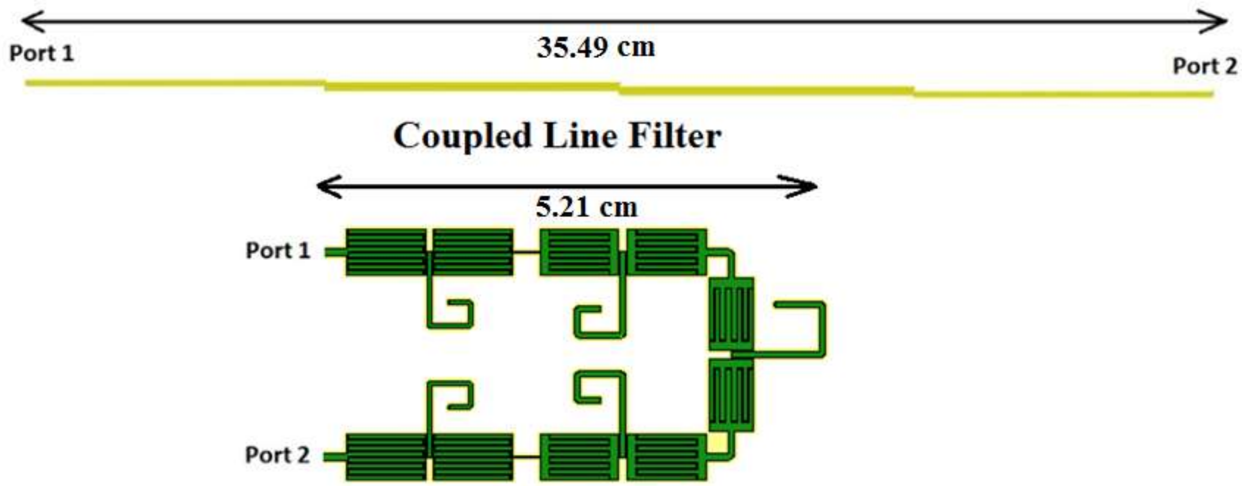


Fig.15.Coupled BPF and MTM-ZOR BPF size comparisons

Dimension wise each resonator length is $\lambda_g/20$ and if we compare with coupled line and hairpin model filters it is 7 times and 3 times smaller.

4.1 MTM-ZOR Band pass filter design for rest of the bands

At the start we have designed and fabricated a MTM-ZOR BPF. We have also discussed how we can control its bandwidth and high frequency skirt. Based on the results of the previous section we modified the filter in the frequency range of 420-520 MHz. Filter design dimensions are given in Table:-2. The fabricated design and its experimental results are given in Fig.16 (Table-3).

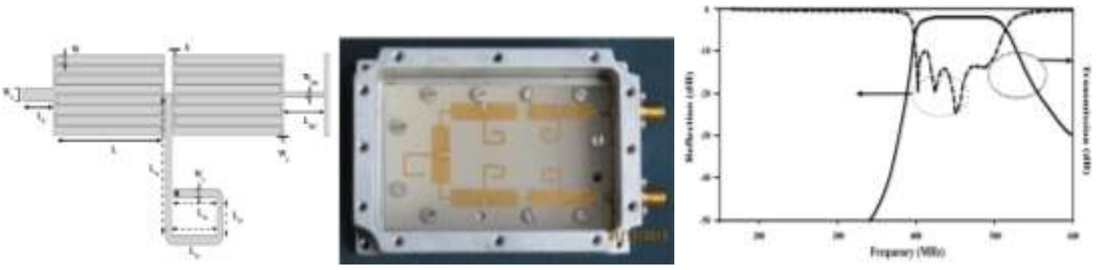


Fig.16. (a) Modified fabricated Design (in Chassis enclosure). (b) Experimental result.

Table: 2

	Design Parameter	420-520 MHz
ZOR-1	W, S, $W_{p,}$ L	0.527,0.11,0.125,8.7595
	W_F, L_F	0.8,5.6
	L_{s1}, L_{s2}, l_{s3}, l_{s4},Ws	8.01,4.005,2.0025,2.0035,0.555
	L_{IRC} ,W_{IRC}	3.1,0.3
ZOR-2	W, S,W_p, L	0.562,0.11,1.35,6.52
	L_{s1}, L_{s2}, L_{s3}, l_{s4},W_s	8.9957,4.49785,2.248925 2.248925,0.69
	L_{IRC} ,W_{IRC}	2.5,0.7
ZOR-3	W, S,W_p,L	0.585,0.11,1.21, 6
	L_{s1}, L_{s2}, L_{s3},W_s	9.9546, 4.9773, 4.9773,0.69
	L_{IRC} ,W_{IRC}	2.5,07

Table:- 3

Design Parameter	Expected	Achieved
Band width(6 dB)	420-520 MHz	411-517 MHz
Insertion loss	-2.0-3.0 dB (470 MHz)	-2 dB (470 MHz)
Return loss	-10 dB over the band	-10 dB over the band
Higher frequency cutoff +30MHz	-30 dB (550 MHz)	-32 dB (547MHz)

After getting in band response of 420-520 MHz sub-band filter, we fabricated the other three subbands (240-340 MHz, 300-400 MHz, and 360-460 MHz). In lower frequency band filters the percentage of bandwidth is more compared to the high frequency band filter. For achieving more percentage bandwidth we used interdigital capacitor gap as much as possible. In low frequency band (240-340 MHz) the gap of the finger should be 0.075mm for achiving 100 MHz bandwidth, but our fabricator could only make a 0.1mm gap of the finger. Hence, we could not achive 100 MHz of bandwidth (Table-4). The design dimesion for all four subbands are given in Table-4.

Table:4

		420-520 MHz	360-460 MHz	300-400 MHz	240-340 MHz
ZOR-1	W, S, W_p, L	0.527,0.11,0.125,8.7595	0.54,0.11,0.16,10.5	0.587,0.1,0.165,11.9	5.45,0.1,0.267,18.364
	W_F, L_F	0.8,5.6	4.5,0.8	0.9,5	0.8, 5
	L_{s1}, L_{s2}, l_{s3}, l_{s4},Ws	8.01,4.005, 2.0025,2.0035,0.555	8.854,4.4595, 2.22745,2.22745,0.555	9.85,4.925, 2.4625,2.4625,0.555	10.85,5.425, 2.7125, 2.7125,0.555
	L_{IRC} ,W_{IRC}	3.1,0.3	4.1,0.3	4.2,0.2	4.2,0.2
ZOR-2	W, S,W_p, L	0.562,0.11,1.35,6.52	0.555,0.11,1,8.67	0.571,0.1,0.9,9.5	0.55,0.1,1.1,14.6
	L_{s1}, L_{s2}, L_{s3}, l_{s4},W_s	8.9957, 4.49785, 2.248925 2.248925,0.69	9.8341,4.9701, 2.4585,2.4583,0.69	11.35,5.675, 2.8375,2.8375,0.69	12.35,6.175, 3.0875, 3.0875,0.69
	L_{IRC} ,W_{IRC}	2.5,0.7	2.5,1	2.5,0.9	2.5,1.2
ZOR-3	W, S,W_p,L	0.585,0.11,1.21	0.54,0.11,0.95,7.763	0.565,0.1,0.8,9	0.56,0.1,1.1,13.9
	L_{s1}, L_{s2}, L_{s3},W_s	9.9546, 4.9773, 4.9773,0.69	10.82,5.14, 2.57,0.69	12.35,6.175, 6.175,0.69	13.35,6.675, 6.675,0.69
	L_{IRC} ,W_{IRC}	2.5,07	2.5,1	2.5,0.9	2.5,1.2

The fabricated design are given in Fig.17. The measured results are given in Fig.18 (Table-5). The measured results are closely matched to our desired response.

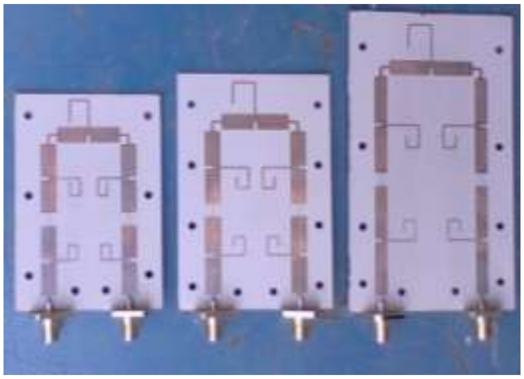


Fig.17. Prototype of three MTM-ZOR filters for 360-460 MHz, 300-400 MHz, and 240-340 MHz,

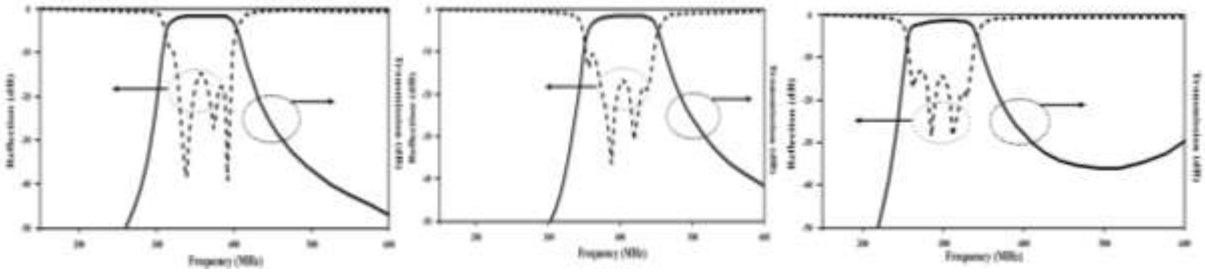


Fig.18. Measured results of MTM-ZOR filters for 360-460 MHz, 300-400 MHz, and 240-340 MHz.

Table-5

Design Parameter	Achieved (*Expected*)	Achieved (Expected)	Achieved (Expected)
Band width(6 dB)	352-454 MHz (360-460 MHz)	311-405 MHz (300-400 MHz)	255-343 MHz (240-340 MHz)
Insertion loss	1.96 dB (400 MHz) (2.0 - 3.0 dB (400 MHz))	1.79 dB (350 MHz) (2.0 - 3.0 dB (350 MHz))	1.81 dB (290 MHz) (2.0 - 3.0 dB (290 MHz))
Return loss	-10 dB over the band (-10 dB over the band)	-10 dB over the band (-10 dB over the band)	-10 dB over the band (-10 dB over the band)

The overlap view of all sub bands (240-340 MHz, 300-400 MHz, 360-460 MHz, and 420-520 MHz) is given Fig.19.

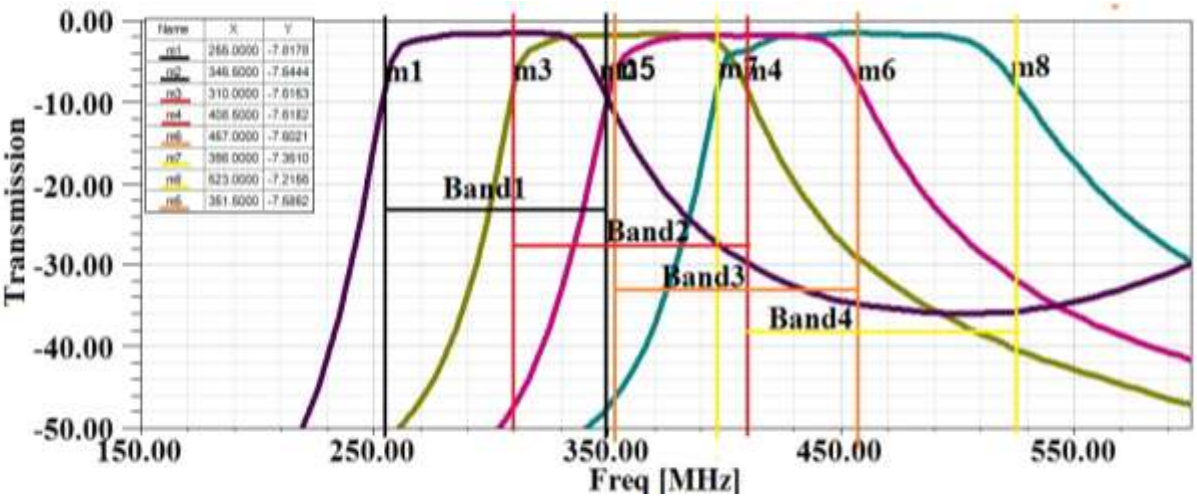
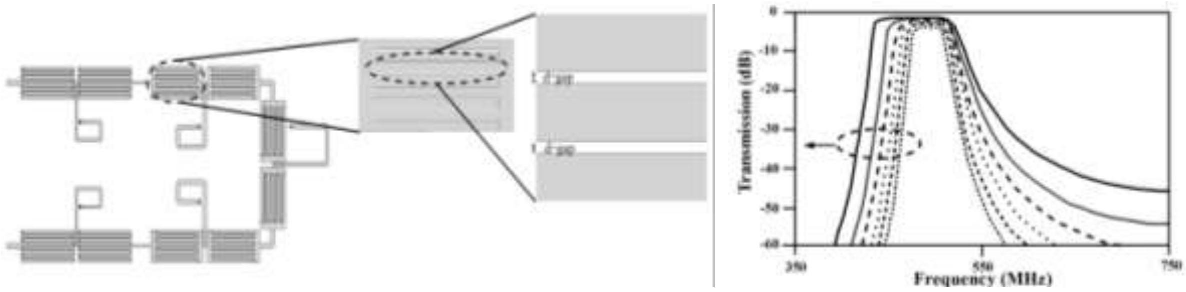


Fig: 19 .250-500 MHz subband Filter overlap view.

4.2 Bandpass filter bandwidth and roll off control

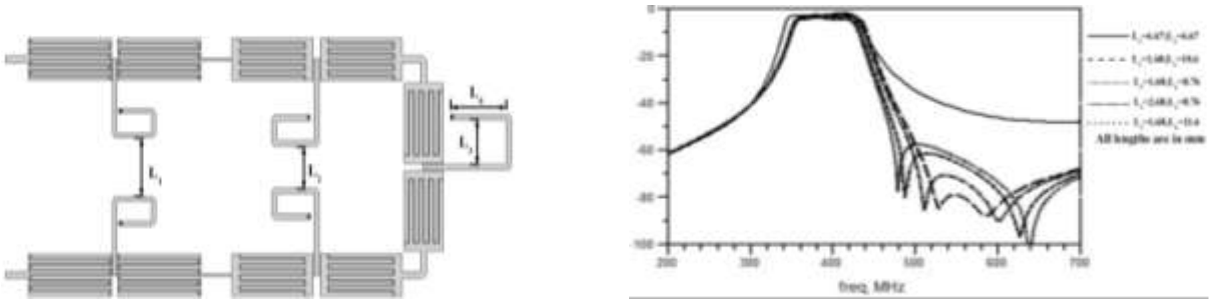
The MTM-ZOR BPF is a combination of interdigital capacitor and shorted strips. Interdigital capacitor is a combination of multiple parallel plate capacitors in series. Closely coupled capacitor will enhance the bandwidth and the higher frequency skirt will decrease and inverse action happens for loosely coupled. Applying the same principle in our filter, we increased the gap length from 0.1 to 0.25 mm, resulting in bandwidth decrease while the high frequency skirt becomes sharper (Fig.20).



(a) (b)

Fig.20. Increasing the gap length affects the MTM-ZOR BPF charecteristics (a) schematic view (b) simulated results.

For making a compact bandpass we added a stub inductor inside, that causes coupling effect between two opposite inductors. The parametric study shows the different gap lengths (L_1, L_2, L_3) that control the high frequency skirt. The Fig.20 shows the different gap lengths and the high frequency skirt effects on the filter response.



(a) (b)

Fig.21. Arragment of gap betweeen inductor affects on MTM-ZOR BPF (a) schematic view (b) simulated results.

This study shows that higher frequency skirt and bandwidth cannot be achived at the same time and that some technical compormise is need. For our GMRT application, bandwidth (100 MHz) is more important than higher frequency skirt selectivity.

5.0 Integrated Bandpass filter

Before this section we have already describe design and development of switch bandpass filter using MTM-ZOR technique for 250-500 MHz sub-band filter (240-340 MHz, 300-400 MHz, 360-460 MHz, 420-520 MHz). Making indivulal filter for all subband is take more space and it is also diffcult to wiring, for simlification we integrated two sub-band filter into a single unit (refred figure-22) and then both two unit are integrated in a single one, over all we have reduce our chassi quanty in a factor of four . The overall integrated response is given Fig.23.

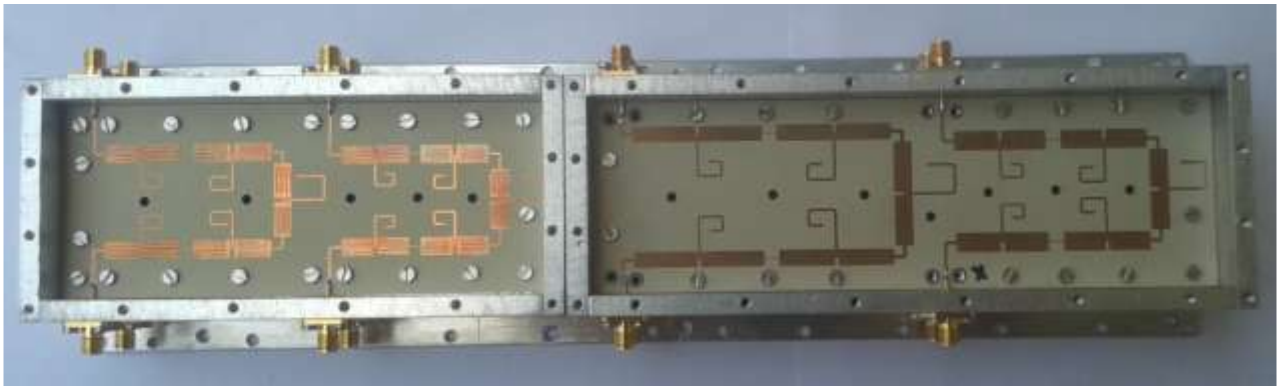


Fig.22. Integrated filter arragemnt for 250-500 MHz sub-band filter.

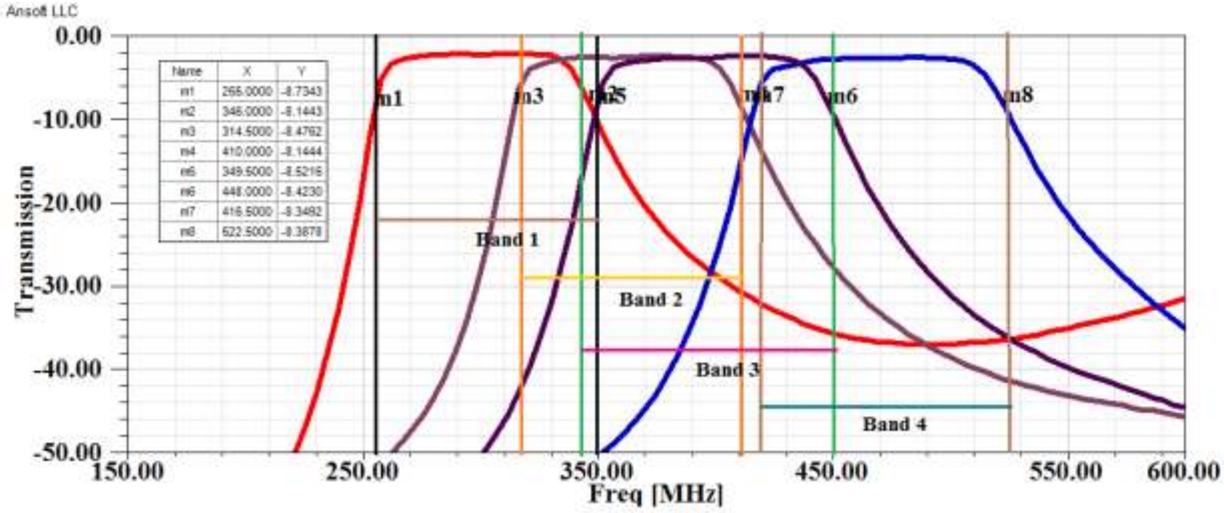


Fig.23. Modified 250-500 MHz subband Filter overlap view.

The comparative analysis of our indivuasl filter and the modifed filter overlap response results is given Fig.24. The figure continuous curve is our modified resonse and the doted one is the previous response of indivual filters. Our observation we found that both the response are closely match there is some few MHz differnce is found in the 360-460 MHz response.

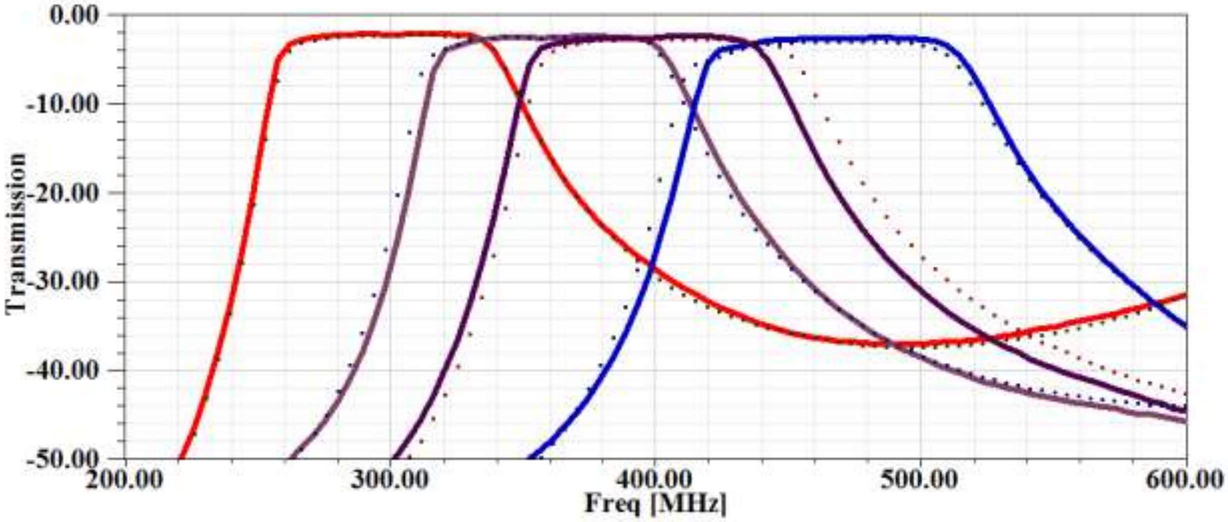


Fig.24. 250-500 MHz subband Filter overlap view (Continues line for Modified and discrete line for previous response).

6.0 Deflection test of C13 antenna for all sub bands

Putting this entire subband filter in C13 antenna, we do the deflection test at antenna base. The results are given in Table-6.

Table-6

Source- CASA.
Expected deflection is 12.7 dB.

Frequency	Deflection (CH1)	Deflection (CH2)
240-340 MHz	9.35 dB	9.75 dB
300-400 MHz	10.01 dB	11.1 dB
360-460 MHz	11.09 dB	11.06 dB
420-520 MHz	9.65 dB	10.83 dB

7.0 Conclusion

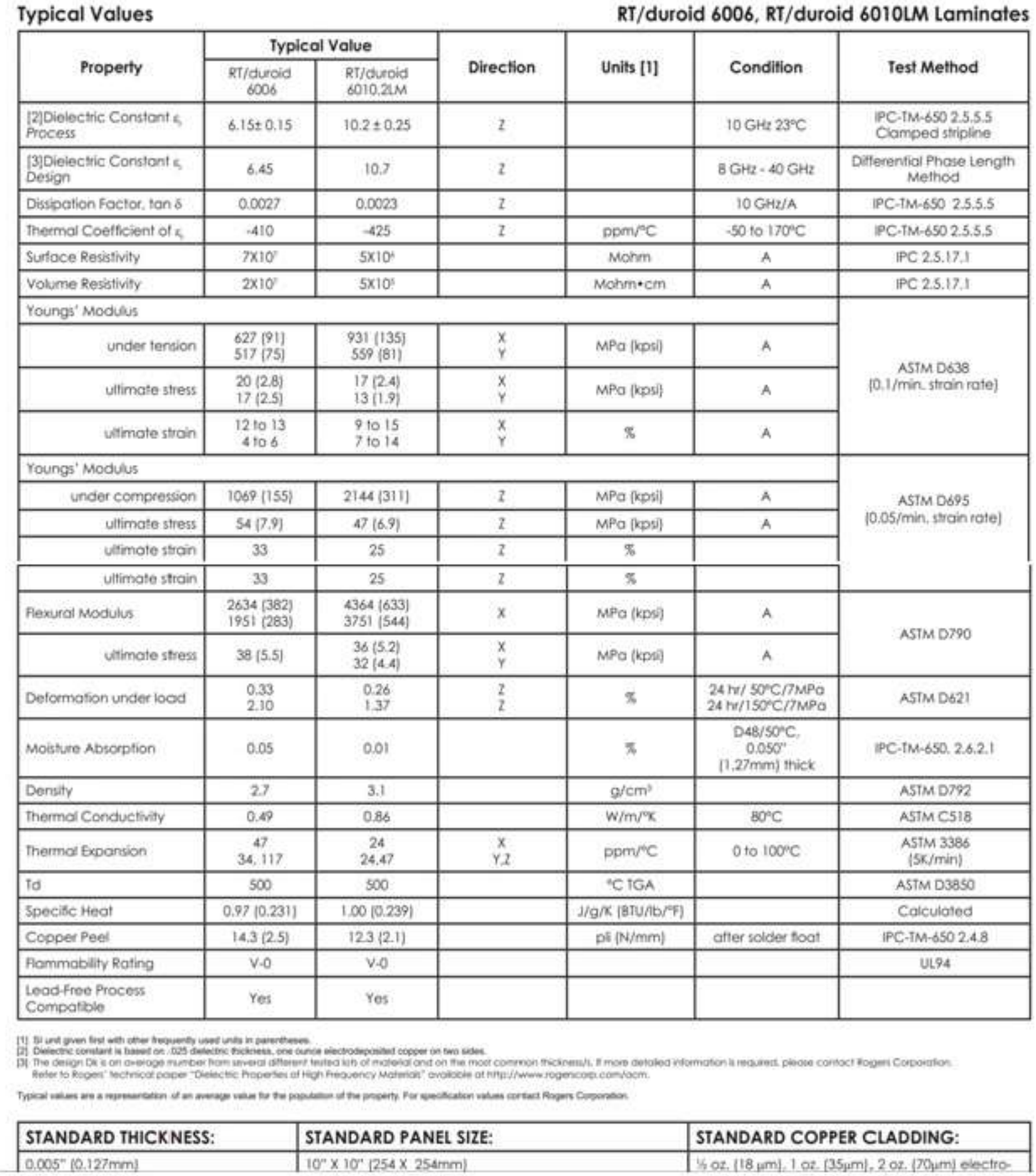
Using the MTM ZOR technique the filter size has reduced at least a factor of four. We could achieve the specified bandwidth of all the sub bands filters with an insertion loss of less than 2 dB and return loss of better than -10 dB. The rejection at 10% of the 6 dB frequency points for all the sub band filters is around -30 dB or better. The integrated filter bank installed on C13 antenna is found to work satisfactorily. This is an unique technique for microstrip design which can be extended for designing antennas, baluns etc.

Reference

[1] Raut, A., Bhalerao,.V, A. Praveen Kumar," Front-end Electronics for the upgraded GMRT ", IOP Conf. Series: Materials Science and Engineering 44 (2013) 012025 doi:10.1088/1757-899X/44/1/012025.
[2] C. Caloz, T. Itoh ," Left-Handed Transmission Lines and Equivalent Metamaterials for Microwave and Millimeter-Wave Applications," Microwave, European Conference - EuMC , 2002.
[3] G.V. Eleftheriades and M.A. Antoniades, "Antenna Applications of Negative-Refractive-Index Transmission-Line (NRI-TL) Metamaterials," Chapter 14 in Modern Antenna Handbook, pp. 677-736, Editor C.A. Balanis, John Wiley & Sons, July 2008.
[4] ATSUSHI SANADA, CHRISTOPHE CALOZ, and TATSUO ITOH "Novel Zeroth-Order Resonance in Composite right/Left handed Transmisson line Resonators," 2003 Asia-Pacific Microwave Conference
[5] G. Jang S. Kahng, "Compact metamaterial zeroth-order resonator bandpass filter for a UHF band and its stopband improvement by transmission zeros." IET Microwaves, Antennas & Propagation, Jan 2011.
[6] J.S.HONG M. J. LANCASTER Microstrip Filters for RF/Microwave Applications2001 John Wiley & Sons, Inc. ISBNs: 0-471-38877-7

Appendix-1

Technical specification of RT/duroid 6010 Laminates



Typical Values **RT/duroid 6006, RT/duroid 6010LM Laminates**

Property	Typical Value		Direction	Units [1]	Condition	Test Method
	RT/duroid 6006	RT/duroid 6010.2LM				
[2]Dielectric Constant ε_r Process	6.15± 0.15	10.2 ± 0.25	Z		10 GHz 23°C	IPC-TM-650 2.5.5.5 Clamped stripline
[3]Dielectric Constant ε_r Design	6.45	10.7	Z		8 GHz - 40 GHz	Differential Phase Length Method
Dissipation Factor, tan δ	0.0027	0.0023	Z		10 GHz/A	IPC-TM-650 2.5.5.5
Thermal Coefficient of ε_r	-410	-425	Z	ppm/°C	-50 to 170°C	IPC-TM-650 2.5.5.5
Surface Resistivity	$7X10^7$	$5X10^6$		Mohm	A	IPC 2.5.17.1
Volume Resistivity	$2X10^7$	$5X10^5$		Mohm•cm	A	IPC 2.5.17.1
Youngs' Modulus						ASTM D638 (0.1/min. strain rate)
under tension	627 (91) 517 (75)	931 (135) 559 (81)	X Y	MPa (kpsi)	A	
ultimate stress	20 (2.8) 17 (2.5)	17 (2.4) 13 (1.9)	X Y	MPa (kpsi)	A	
ultimate strain	12 to 13 4 to 6	9 to 15 7 to 14	X Y	%	A	
Youngs' Modulus						ASTM D695 (0.05/min. strain rate)
under compression	1069 (155)	2144 (311)	Z	MPa (kpsi)	A	
ultimate stress	54 (7.9)	47 (6.9)	Z	MPa (kpsi)	A	
ultimate strain	33	25	Z	%		
ultimate strain	33	25	Z	%		
Flexural Modulus	2634 (382) 1951 (283)	4364 (633) 3751 (544)	X	MPa (kpsi)	A	ASTM D790
ultimate stress	38 (5.5)	36 (5.2) 32 (4.4)	X Y	MPa (kpsi)	A	
Deformation under load	0.33 2.10	0.26 1.37	Z Z	%	24 hr/ 50°C/7MPa 24 hr/150°C/7MPa	ASTM D621
Moisture Absorption	0.05	0.01		%	D48/50°C, 0.050" (1.27mm) thick	IPC-TM-650, 2.6.2.1
Density	2.7	3.1		g/cm³		ASTM D792
Thermal Conductivity	0.49	0.86		W/m/°K	80°C	ASTM C518
Thermal Expansion	47 34, 117	24 24,47	X Y,Z	ppm/°C	0 to 100°C	ASTM 3386 (5K/min)
Td	500	500		°C TGA		ASTM D3850
Specific Heat	0.97 (0.231)	1.00 (0.239)		J/g/K (BTU/lb/°F)		Calculated
Copper Peel	14.3 (2.5)	12.3 (2.1)		pli (N/mm)	after solder float	IPC-TM-650 2.4.8
Flammability Rating	V-0	V-0				UL94
Lead-Free Process Compatible	Yes	Yes				

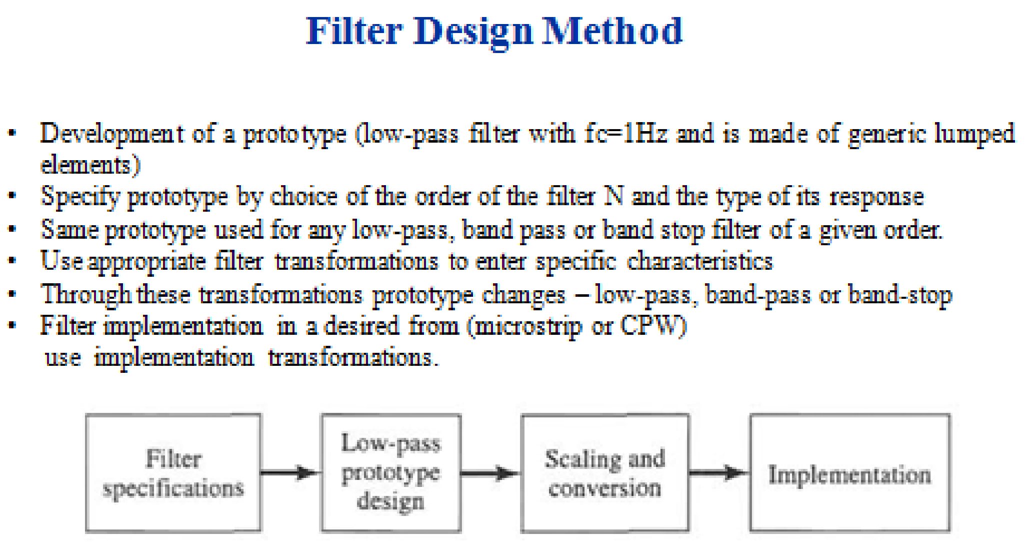
[1] SI unit given first with other frequently used units in parentheses.
[2] Dielectric constant is based on .025 dielectric thickness, one ounce electrodeposited copper on two sides.
[3] The design Dk is an average number from several different tested lots of material and on the most common thickness/s. If more detailed information is required, please contact Rogers Corporation. Refer to Rogers' technical paper "Dielectric Properties of High Frequency Materials" available at http://www.rogerscorp.com/acm.

Typical values are a representation of an average value for the population of the property. For specification values contact Rogers Corporation.

STANDARD THICKNESS:	STANDARD PANEL SIZE:	STANDARD COPPER CLADDING:
0.005" (0.127mm)	10" X 10" (254 X 254mm)	½ oz. (18 µm), 1 oz. (35µm), 2 oz. (70µm) electro-

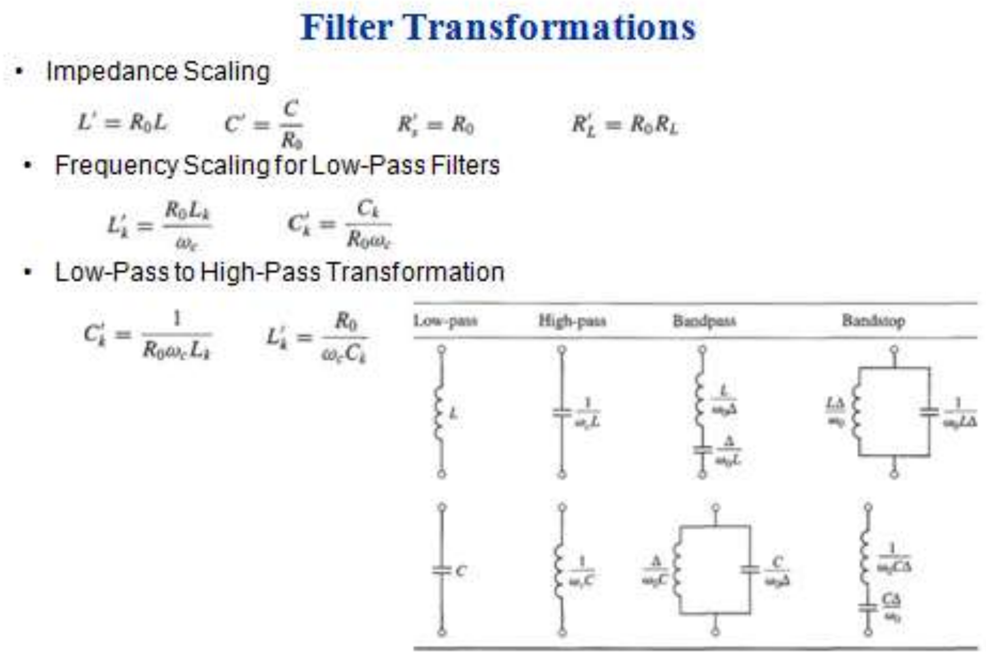
Appendix-2

The conversions of lumped elements to distributed components are as fallow;-



Filter Design Method

- Development of a prototype (low-pass filter with fc=1Hz and is made of generic lumped elements)
- Specify prototype by choice of the order of the filter N and the type of its response
- Same prototype used for any low-pass, band pass or band stop filter of a given order.
- Use appropriate filter transformations to enter specific characteristics
- Through these transformations prototype changes – low-pass, band-pass or band-stop
- Filter implementation in a desired from (microstrip or CPW)
  use implementation transformations.



Filter Transformations

- Impedance Scaling

$$L' = R_0 L \qquad C' = \frac{C}{R_0} \qquad R_s' = R_0 \qquad R_L' = R_0 R_L$$

- Frequency Scaling for Low-Pass Filters

$$L_k' = \frac{R_0 L_k}{\omega_c} \qquad C_k' = \frac{C_k}{R_0 \omega_c}$$

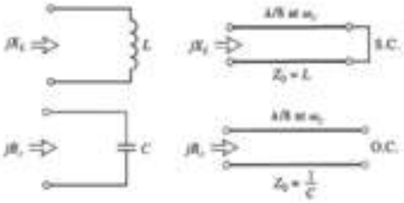
- Low-Pass to High-Pass Transformation

$$C_k' = \frac{1}{R_0 \omega_c L_k} \qquad L_k' = \frac{R_0}{\omega_c C_k}$$

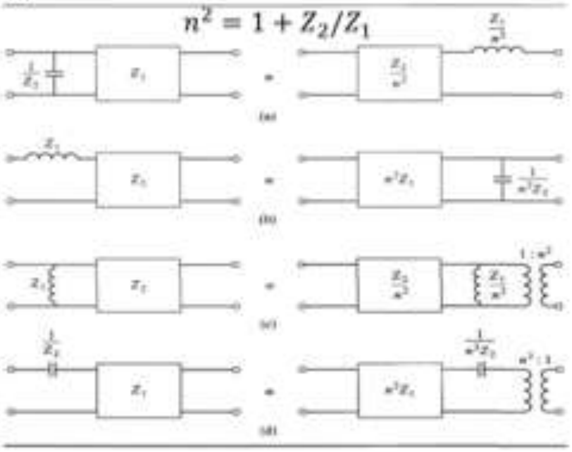
Filter Implementation

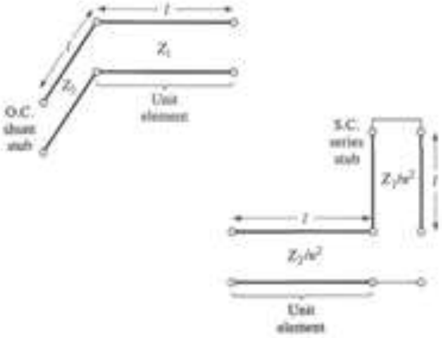
- Richards' Transformation

$$jX_L = j\Omega L = jL\tan\beta\ell \qquad jB_C = j\Omega C = jC\tan\beta\ell$$



- Kuroda's Identities
  - Physically separate transmission line stubs
  - Transform series stubs into shunt stubs or vice versa
  - Change impractical characteristic impedances into more realizable ones





Design Steps

- Lumped element low pass prototype (from tables, typically)
- Convert series inductors to series stubs, shunt capacitors to shunt stubs
- Add λ/8 lines of Zo = 1 at input and output
- Apply Kuroda identity for series inductors to obtain equivalent with shunt open stubs with λ/8 lines between them
- Transform design to 50Ω and fc to obtain physical dimensions (all elements are λ/8).