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Spurious Coupling Mitigation in Liquid Crystal Polymer Based Microstrip Filter at Q-Band

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Abstract—RF and mm-wave filters suffer from a common problem of asymmetries in filter transmission response caused by unwanted field couplings between individual resonators. In this paper, unwanted or spurious couplings between non-adjacent resonators are identified in the filter network from the simulation stage and mitigated to the extent possible. A 4-pole Quasi Elliptic Planar Band Pass Filter is fabricated at 48.5 GHz on a Liquid Crystal Polymer (LCP) substrate. An improvement of 6 dB in sidelobe imbalance in filter transmission response is obtained. EM simulation demonstrates the effect of spurious coupling on bandpass filter transmission response. Commensurate measurement results are presented.

1. INTRODUCTION

The satellite system involves a significant number of filtering stages at various steps for efficient conditioning of input signal. Filters at input stages are mainly required for desired frequency band selection along with pre-specified immediate and far out of band rejections. Insertion loss at mid-stages of a satellite signal chain is not critical, and hence the communication systems can tolerate a planar filter having a little higher insertion loss. A typical signal chain of a satellite transponder is shown in Fig. 1.

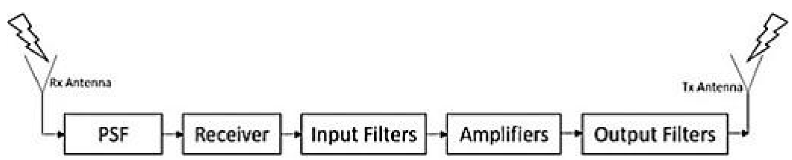

Figure 1. Simplified block diagram of satellite signal chain.

Planar filters are widely employed in mid-stages for the band selection in various satellite payloads. These filters need to be carefully designed for the intended electrical response. Unwanted electromagnetic field couplings (also called spurious coupling) between non-adjacent resonators play a significant role in the realized planar filters' electrical performance. Spurious coupling causes significant alteration in the filter's transmission response and ultimately degrades out of band rejection performance of the filter, which is one of the critical aspects of filter design. The design and development of a microstrip bandpass filter on liquid crystal polymer (LCP) have been widely reported [1–6]. Quasi-elliptic filters as reported in [1] suffered more than 10 dB of sidelobe imbalance, which ultimately degrades near out of band rejection performance of the filter. The electrical performance in most

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of these reported realizations suffered from poor out of band performance. This paper presents a 4-pole quasi-elliptic filter on an LCP substrate at Q-band. The general technique used to identify and mitigate undesired coupled field interactions between non-adjacent resonators is described in detail. The reported design technique results in an improved filter's transmission response, and it is independent of frequency band and type of resonators. Considering spurious coupling from the design stage helps in improved simulation and subsequent realization of the filter. Split ring resonators are used for filter realization. CST filter design tool is used for the identification and extraction of spurious field coupling.

The novelty of the work lies in the inclusion of spurious coupling identification and mitigation from the simulation stage which results in the realization of the filter hardware with a near-symmetrical transmission response. Undesired asymmetries unnecessarily force over designing of the filter circuit (increased filter order or pole) which can be avoided with the suggested technique. At high frequencies i.e., Q-band, undesired couplings may dominate the desired field coupling and make it very difficult to realize a desired performance from the filter, and in such cases the suggested identification and mitigation process becomes useful. The suggested technique is not exclusively reported in any of the available literature to the best of the authors' knowledge for such high frequency applications. In Section 2, filter design and simulation are discussed. Section 3 is devoted to the discussion on the fabricated filter and their measured electrical response, and Section 4 concludes the work done in the paper.

2. SYNTHESIS & SIMULATION

Cascaded quadruplet topology as shown in Fig. 2 is chosen for the realization of the filter having electrical specifications as per Table 1. From the filter's transmission/reflection response synthesis, it is concluded that a four-pole filter is sufficient to achieve the targeted specifications of Table 1. The position of transmission zeroes is chosen to be symmetric at $\pm 1.45 * j$ in low pass prototype synthesis.

Table 1. Synthesis parameters for the targeted specifications.

Parameters	**Value**
Filter Order	4
Transmission zeros	2 nos., $\pm 1.45 * j$
Return loss	18 dB
Bandwidth	3 GHz
Topology	Cascaded Quadruplet (CQ)

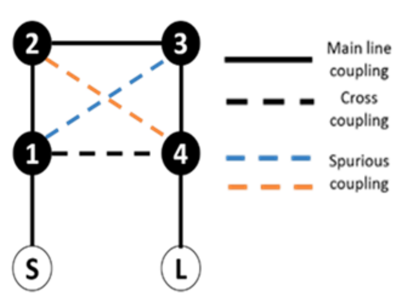

Figure 2. Cascaded Quadruplet (CQ) Filter Topology.

Quasi-elliptic filtering function response is realized using split ring resonators. Realized 3-dB fractional bandwidth of the filter is 6% at Q-band. The obtained inter resonator coupling (m_{ij}, $i = 1:4$, $j = 1:4$, $i \neq j$) values were calculated as per the method given in [7, 8] and are shown in Table 2. These values are verified in ADS circuit simulation. Only the nonzero values for the inter resonator

Table 2. Normalized coupling values.

Normalized Matrix Elements			
$m_{1,1}$	0	$m_{1,2} = m_{2,1}$	0.950202
$m_{2,2}$	0	$m_{1,4} = m_{4,1}$	-0.31993
$m_{3,3}$	0	$m_{2,3} = m_{3,2}$	0.876096
$m_{4,4}$	0	$m_{3,4} = m_{4,3}$	0.950202
$m_{S,1} = m_{1,S}$	1.12986	$m_{4,L} = m_{L,4}$	1.12986

coupling values are shown in the table while zero values are shown only for self-coupling (m_{ii}). Here '0' self-coupling values represent synchronously tuned resonators.

Synthesized coupling matrix is verified in ADS circuit simulator, and resultant filter response is as shown in Fig. 3. The rounding of the transmission response edges and poor sharpness of the transmission zeros is attributed to the poor Q of the microstrip structure. Resonators of the filter are required to be kept in certain topology, i.e., cascaded quadruplet (CQ), canonical, etc. The placement of the resonators in a filter structure encompass desired filed coupling along with undesired field couplings. Bandpass filters are prone to unwanted fields coupling called spurious couplings [9–16]. These unwanted spurious couplings produce undesired asymmetries in the filter transmission response, leading to poor out of band rejection, and at times becomes unacceptable. Three development cases for the filter are simulated to demonstrate the suggested mitigation technique. Simulated filter models and their transmission responses are shown in Figs. 4 & 5, respectively.

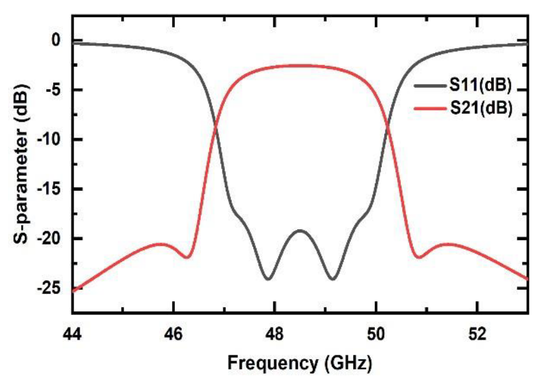

Figure 3. Circuit synthesis response.

Case 1: Initially, a 4-pole filter is modelled in ADS, and the individual resonators are characterized as per the group delay method suggested in [1]. The filter model is as shown in Fig. 4. The imbalance between the sidelobe levels of the transmission response is around 11 dB as shown in Fig. 5, which is high and causes significant asymmetry between filter skirts on both sides of the filter centre frequency. Such imbalances are attributed to the undesired coupling between non-adjacent resonators as suggested in [1]. The proximity between adjacent and non-adjacent resonators is constrained by the amount of required coupling between corresponding resonators. The obtained filter response was compared with the ideal filter response in the CST filter designer tool, and obtained coupling values are listed in Table 3. Values of cross-coupling between resonators 1(2) & 3(4) are significant.

Case 2: To reduce the undesired couplings between resonators 1 and 3 along with 2 and 4 as suggested in Fig. 1, we increased the distance between resonators 1 and 4 and introduced a high impedance U-shaped line. This U-shaped line helps to reduce the proximity between non-adjacent resonators (1 & 3 and 2 & 4) but still provides the desired cross-couplings between resonators 1 and 4. It is clear from the obtained response in Fig. 5 that the sidelobe imbalance has been reduced to

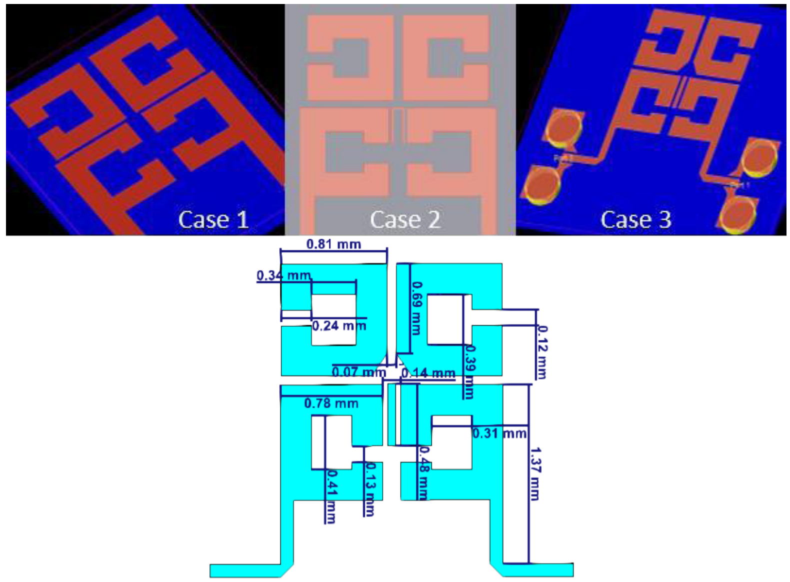

Figure 4. Simulation model in ADS (Case 1, 2 & 3) & filter parameters (Case 3).

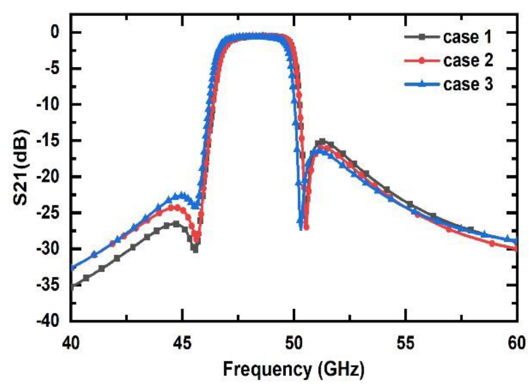

Figure 5. Simulation results of the filter in ADS.

approximately 8 dB level from 11 dB as shown in case 1. The fabrication of a very high impedance line becomes challenging from the lithography point of view, and hence, further, improvement is explored in case 3.

Case 3: To improve the sidelobe response further, a small change in resonators 2 and 3 was done, and they were chamfered at the edges near the high impedance line, which decreased the fringing E-field being coupled to resonators 1 and 4 from resonators 3 and 2, respectively. The difference in sidelobe level has decreased further from 8 dB level to 6 dB approximately, while other parameters like bandwidth and group delay are minutely affected. It is clear from these simulation model corrections that the unwanted couplings can be minimized by tweaking the shape of the resonators and thereby minimizing the unwanted fringing fields available for spurious coupling. The filter is simulated with the G-S-G pad in place so that the measurement can be performed using a GSG probe.

Improvements obtained over these cases have been put together for comparison in Fig. 5. Table 3 enlists the desired and undesired coupling for all the three cases. These values are obtained using the CST filter designer. It is evident from the table that the spurious coupling is reduced from case 1 to case 3. While the spurious coupling decreased, the desired coupling values change is minimal and is shown in Fig. 6 and Table 4.

Table 3. Obtained coupling values.

Case 1	Case 2	Case 3
Normalized Matrix Elements	**Normalized Matrix Elements**	**Normalized Matrix Elements**
$m_{1,1} = -0.0208605$	$m_{1,1} = 0.0578683$	$m_{1,1} = 0.228985$
$m_{2,2} = -0.0236751$	$m_{2,2} = -0.0214562$	$m_{2,2} = 0.169641$
$m_{3,3} = -0.00197933$	$m_{3,3} = -0.00562729$	$m_{3,3} = 0.203847$
$m_{4,4} = 0.0183486$	$m_{4,4} = 0.0847814$	$m_{4,4} = 0.255798$
$m_{S,1} = m_{1,S} = 1.11921$	$m_{S,1} = m_{1,S} = 1.1506$	$m_{S,1} = m_{1,S} = 1.08283$
$m_{1,2} = m_{2,1} = 0.884602$	$m_{1,2} = m_{2,1} = 0.894352$	$m_{1,2} = m_{2,1} = 0.847711$
$\boldsymbol{m_{1,3} = m_{3,1} = 0.113518}$	$\boldsymbol{m_{1,3} = m_{3,1} = 0.106897}$	$\boldsymbol{m_{1,3} = m_{3,1} = 0.0679018}$
$m_{1,4} = m_{4,1} = -0.318077$	$m_{1,4} = m_{4,1} = -0.329741$	$m_{1,4} = m_{4,1} = -0.343705$
$m_{2,3} = m_{3,2} = 0.779719$	$m_{2,3} = m_{3,2} = 0.781011$	$m_{2,3} = m_{3,2} = 0.810888$
$\boldsymbol{m_{2,4} = m_{4,2} = 0.113518}$	$\boldsymbol{m_{2,4} = m_{4,2} = 0.106897}$	$\boldsymbol{m_{2,4} = m_{4,2} = 0.0679018}$
$m_{3,4} = m_{4,3} = 0.896038$	$m_{3,4} = m_{4,3} = 0.902239$	$m_{3,4} = m_{4,3} = 0.85205$
$m_{4,L} = m_{L,4} = 1.11921$	$m_{4,L} = m_{L,4} = 1.1506$	$m_{4,L} = m_{L,4} = 1.08283$

Table 4. Variation in inter resonator coupling values.

Couplings	Ideal	Case1	Case2	Case3
$\boldsymbol{m_{S,1} = m_{1,S}}$	1.12986	1.11921	1.1506	1.08283
$\boldsymbol{m_{1,2} = m_{2,1}}$	0.950202	0.884602	0.894352	0.847711
$\boldsymbol{m_{1,4} = m_{4,1}}$	−0.31993	−0.31807	−0.32974	−0.34371
$\boldsymbol{m_{2,3} = m_{3,2}}$	0.876096	0.779719	0.781011	0.810888
$\boldsymbol{m_{3,4} = m_{4,3}}$	0.950202	0.896038	0.902239	0.85205
$\boldsymbol{m_{4,L} = m_{L,4}}$	1.12986	1.11921	1.1506	1.08283

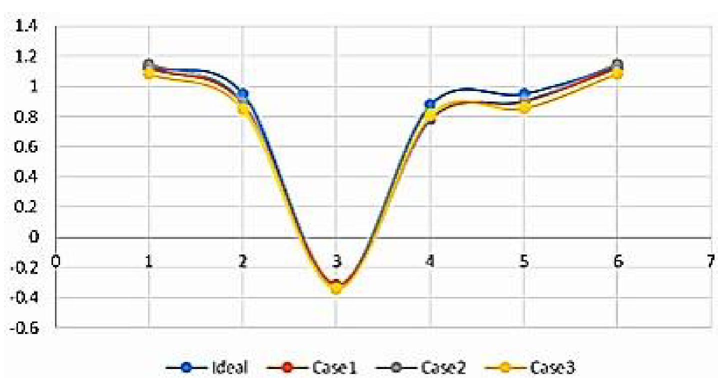

Figure 6. Coupling variation between resonators (All cases).

3. FABRICATION AND RESULTS

The fabricated filter is as shown in Fig. 7 on a Rogers ULTRALAM 3850 HT sheet. The thickness of the substrate is 100 µm (dielectric constant = 3.15). G-S-G probe is utilized for measurement. Ground pads are shorted to the ground plane through "Vias" made of silver epoxy. The measured filter response

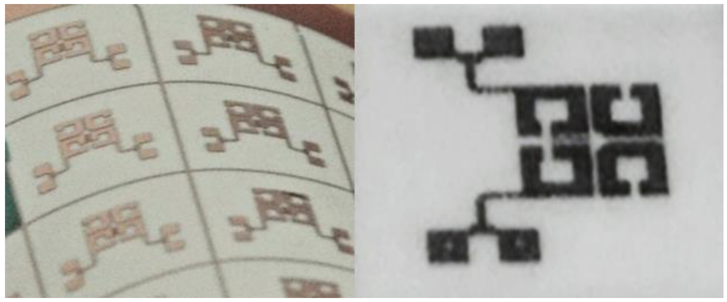

Figure 7. Fabricated filter on LCP substrate.

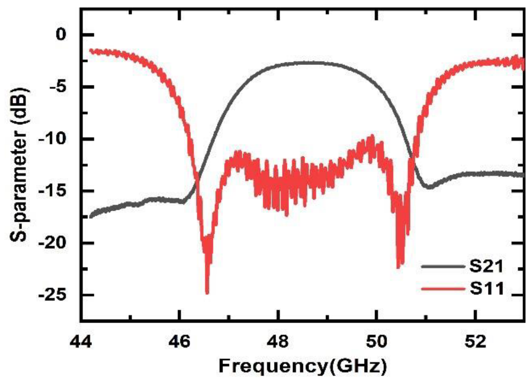

Figure 8. Measured LCP filter electrical performance.

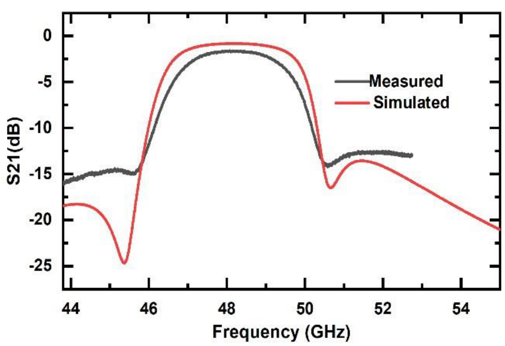

Figure 9. Comparison of the simulated V/s measured response.

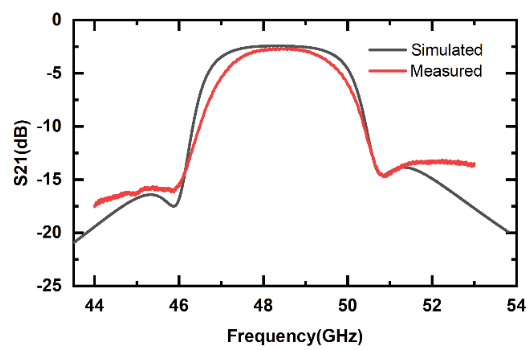

Figure 10. Comparison between measured and back simulated transmission response.

using the G-S-G probe is as given in Fig. 8. The transmission response appears to be narrowband compared to what is expected from simulations and rounding of the transmission frequency response at the band edges observed which results from the finite Q. The sidelobe level of the realized filters is near-symmetrical and is attributed to the structural changes performed at the time of the simulation. The measured transmission response is compared with the simulated 3D EM response obtained from CST (for the model shown in Case 3) in Fig. 9. A close correlation is obtained between measured and simulated response and transmission response side-lobe levels. Insertion loss in the measured case is higher than the simulated case, and it can be attributed to the poor RL and finite surface roughness of the rolled copper on LCP. Sidelobe levels in the measured case are slightly distinct from the simulated response due to stronger cross-coupling between resonators (1 and 4) and can be attributed to the limited control over fabrication tolerance at such high frequency (small wavelength).

The measured response is more symmetric than the 3D EM simulated response as shown in Fig. 9. The reason for the better symmetry is the presence of less amount of spurious coupling between non-adjacent resonators. The simulated 3D EM model is modified to obtain a close match with respect to measured response, and obtained back-simulated response is shown in Fig. 10.

The coupling parameters as shown in Table 5 are modified compared to case 3 to obtain a close match between measured and back-simulated responses. As explained earlier, stronger cross-coupling is present in the measured response which causes reduced rejection through sidelobe levels. The spurious coupling is less than Case 3 in the measured response, and hence the obtained symmetry is much better than the 3D EM simulated case.

Table 5. Modified parameters for 3D EM simulation.

Couplings	**Back simulated response**
$m_{S,1} = m_{1,S}$	1.0254
$m_{1,2} = m_{2,1}$	0.7710
$m_{1,4} = m_{4,1}$	**−0.4733**
$m_{2,3} = m_{3,2}$	0.8133
$m_{3,4} = m_{4,3}$	0.7710
$m_{4,L} = m_{L,4}$	1.0254
$M_{1,3} = M_{2,4}$	**0.0379**

4. CONCLUSIONS

The design and development of wideband microwave and millimetre wave devices with accurate performance is highly desirable for satellite applications. A 4-Pole Quasi-Elliptic Band Pass Filter at Q-band is realized on a liquid crystal polymer substrate. The spurious couplings present between non-adjacent resonators are identified and mitigated with the corresponding changes in filter resonator structures. Computer added identification of spurious coupling with the help of CST filter designer is performed which can be very useful for the improved filter design of higher-order.

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