Compact Band-Pass Filter with Controllable Frequency Characteristics

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Abstract

A compact microstrip tunable bandpass filter (BPF) is proposed and investigated. The filter synthesis and structure are based on parallel microstrip lines that are printed over an RT/duroid 6006/6010LM substrate, with a permittivity of 10.2 and thickness of 1.27mm. A parallel topology method can be adjusted for the filter tunability in the center frequency, to allow fully tuned frequency response. In order to tune the targeted pass band frequency, a lumped element capacitor is used. This capacitor was optimally located over the middle strip resonator. The pass band frequency was smoothly shifted downwards from 2.4GHz to 1.8GHz, when the capacitance of the capacitor varies from 0.15pF to 0.9pF. The proposed filter demonstrates in-band insertion loss of around 0.25 dB and return loss better than 20 dB over the whole pass band frequency. This presents the filter as a favourable candidate for numerous smart future applications.

1 Introduction

The evolution of 4G cellular systems towards the first 5G milestone is increasingly creating the need for the design of compact and multiband microwave bandpass filters [1–2] that can provide RF connectivity within a multimode wireless networking environment. Planar filters are attractive due to their reduced size, ease of fabrication, and offering lower cost. To reduce the size of the filters and improve their performance, researchers have proposed various configurations such as using DGS structures [3–4], employing transmission lines and open-ended stubs [5], and using microstrip periodic stepped-impedance ring resonators [6]. Although these filters have achieved a size miniaturization, their passband responses are fixed and cannot be altered. However, a modern transceiver system requires reconfigurability to enable multi-mode and multi-band operation within a heterogeneous networking ecosystem. Tuned RF bandpass filters, including microstrip filters, are important key components for practical RF front-ends in which become a hot topic of research interest. These bandpass filters are required to be agile and have controllable responses, capable of covering a broad frequency range, in addition to beneficial attributes such as small size and low fabrication cost. Generally, to implement tuning mechanism, various tuning elements are used, that can be classified under piezoelectric transducer (PET) type components[7], RF microelectromechanical systems (MEMS) [8], ferroelectric, magnetic and liquid crystal (LC) materials [9–11]. On the other hand, such diverse tuning configurations may not be able to maintain a broad tuning range and constant absolute bandwidth, while reconfiguring the operating frequency. A solution to avoid such an issue is to use the varactor diode (Varicap) as a candidate tuning mechanism. In addition to the capability of accomplishing wide tuning range, the varactor diodes offer additional benefits, since they are tunable, low cost and can be easily connected or integrated with other components in planar technology. Thus, several varactor tuned BPF have been reported [12–15]. However, most of the modern wireless systems, and in particular the smart phones require a device that operates over multiple systems such as GSM1800MHz, UMTS2200MHz and WLAN2400MHz, in which none of the devices in [12–15] meet this goal. Therefore, this paper proposes a small bandpass filter with continuous wide tuning pass band response from 2.4GHz down to 1.5GHz. The proposed tunable BPF obtains a broader tuning pass band range compare to designs proposed in [7–15], moreover, the simple structure and synthesis of the proposed filter was chosen as it comes up with lower cost and less complexity in contrast to [7–11].

2 Filter Design and Procedure

The proposed tunable bandpass (BPF) filter consists of parallel resonators printed over RT/duroid 6006/6010LM substrate size of 40x 20mm, with a thickness of 1.27mm, and permittivity of 10.2 as illustrated in Figure 1. The used substrate is positioned over copper sheet ground plane dimensions of 40x 20mm. Two I/O feeding lines made of parallel microstrip lines were located at the edges with characteristic impedance of 50Ω as depicted in Figure 1. The full dimension of the proposed filter is given in Table 1. To initially clarify the design concept of the present bandpass filter, it was designed and investigated without the attached capacitor. The design process starts by performing a number of simulations and modifications of the structure and geometry of the proposed bandpass filter; this is done in order to enable the BPF to operate at the 2.4 GHz point.

Keywords: tunable BPF; wide tuning range; parallel transmission lines; varactor device.
Figure 1. Filter synthesis: (a) 3D view, (b) top view

Table 1: The full dimension of the BPF.

| Parameters | Value in mm |
|------------|-------------|
| W1, W2    | 17          |
| W3, W4    | 2           |
| W5, W6, W7| 1.5         |
| L1, L3    | 15          |
| L2        | 20          |
| S1, S2    | 0.25        |
| L, W      | 20, 40      |
| Cp        | 10          |

Figure 2. The S11 and S21 results of unloaded proposed filter

It was observed in Figure 2, that the BPF without the loaded capacitor operates in single narrow band at around WLAN5GHz with an |S11| value bettering -10 dB and with 0.25dB insertion loss. Still, this band does not meet the design objective, namely wide tuning pass band range from 2.4GHz to 1.8GHz. Therefore, a lumped capacitor was used to downshift the resonant frequency, to align with the targeted frequency range of this work. The analysis and performance of the present BPF are obtained using the HFSS software package [16].

Moreover, to come up with the best filter performance, it was interesting to select the best and ideal substrate material. Thus, within this study four substrate materials were examined and analysed as shown in Figure 3. These are (FR4 εr = 4.4), (Roger RT 4003 εr = 3.55), (Silicon-nitrate εr = 7) and (RT/duroid 6010 εr = 10.2). From Figure 3, it should be seen that the proposed BPF exhibits very low insertion loss of around 10.5dB as well as unacceptable return loss of 4.5dB when the filter is printed over FR4 material. In addition, when Roger RT 4003 and Silicon-nitrate were used, the BPF demonstrates acceptable insertion loss, but has only 9 dB return loss.

Moreover, the proposed filter operates at 4.5GHz and 3.5GHz, which does not meet the targeted frequency of 5GHz. In essence, by investigating the three above-mentioned materials, the proposed filter did not manage to achieve acceptable in-band performance in terms of both S11 and S21. However, when RT/duroid 6010 was exploited, a smooth in-band performance in terms of S11 and S21 was accomplished as indicated in Figure 3. This concludes that the RT/duroid 6010 substrate was selected as the optimum material to be used within this study.

3 Results and Discussions

The proposed BPF was loaded with a lumped element capacitor in order to obtain a very wide tuning pass band range. The lumped capacitor was located over the middle strip as depicted in Figure 1,b. The return loss (S11) and insertion loss (S21) of the proposed tunable bandpass filter are indicated in Figure 4. By optimally selecting the proper location of the lumped capacitor, the tuned BPF with a wide tuning range is proposed. It should be noted that by varying...
the capacitance of capacitor from 0.15 pF to 0.9 pF, the pass band frequency of the BPF could be shifted downwards from 2.4GHz to 1.8GHz, covering several different services such as GSM, UMTS and WLAN. The obtained wide pass band demonstrates a very low insertion loss (\(<0.25 \text{ dB}\)), good return loss below 21 dB, while maintaining a size reduction of the whole device.

To further validate how the best location of the attached capacitor was effectively selected, an examination of the capacitor position over the proposed filter was implemented. Three carefully chosen capacitor values, i.e. 0.15, 0.35 and 0.9pF for the operating frequencies of 2.4, 2.2 and 1.8 GHz were considered, respectively, that covers the aggregate bandwidth of the frequency band as shown Figures 5, 6, and 7. The influence of the capacitor position was studied by checking the variations of both the in-band insertion loss \(S_{21}\) and return loss \(S_{11}\) against the location of the lumped capacitor for the previously abovementioned capacitance values.

As one can note, the capacitor position \((C_p)\) was examined by moving the attached capacitor from the up edge down to the middle of the middle parallel strip, i.e. from 2mm to 14mm, with an increment of 4mm steps. when the proposed BPF is loaded with 0.15pf, the filter does not meet the targeted frequency of 2.4GHz, while the capacitor was positioned at 2mm, 6mm and 14mm. However, the desired frequency response at WLAN2.4GHz was perfectly accomplished \((S_{11} \approx 22\text{dB}; \quad S_{21} \approx 0.25\text{dB})\), when the capacitor was fixed at the position of 10mm as indicated in Figure5.

![Figure 5. Capacitor position variation against S11 and S21, loaded with C = 0.15 pF](image)

In the case when the present filter is loaded with 0.35pf, the filter shows impedance matching when the capacitor is positioned at 2mm and 6mm.

![Figure 6. Capacitor position variation against S11 and S21, loaded with C = 0.35 pF](image)

However, it does not meet the targeted frequency of UMTS2.2GHz; whereas when the capacitor is located at 10mm over the middle strip, the impedance matching was seamlessly matched, in which the proposed BPF operates at 2.2GHz with 22 dB return loss and around 0.25 dB insertion loss as depicted in Figure 6.

In the scenario of the 0.9 pf loaded capacitor, the filter shows impedance mismatching when the capacitor is positioned at 6mm; while achieves good impedance matching when it is at 2mm and 14mm, but the filter does not meet the desired frequency of GSM1.8GHz. On the other hand, when the...
lumped capacitor was fixed at 10mm, the present BPF obtains the targeted band of GSM1.8GHz as shown in Figure 7.

Figure 7. Capacitor position variation against S11 and S21, loaded with C = 0.9pF

In order to validate the outcomes in Figure 4, the current distribution of propose filter was illustrated in Figure 8. The capacitor values of 0.15, 0.35 and 0.9 Pf with three operating frequencies, i.e. 2.4, 2.2 and 1.8 GHz were checked and studied. It is clear, that in the case of the 0.15pF loaded capacitor, the current does not flow from port 1 to port 2 at UMTS2.2GHz and GSM1.8GHz, but shows presence at the WLAN2.4GHz as shown in Figure 8,a.

In the paradigm of the 0.35pf loaded filter, the current goes through from port 1 to port 2 at UMTS2.2GHz, while it does not allow the current to pass at both frequencies of WLAN2.4GHz and GSM1.8GHz as depicted in Figure 8, b. Lastly, when the 0.9pF was used, the filter shows smooth current flow from port 1 to port 2 at GSM1.8GHz, while the current was much reduced at WLAN2.4GHz and UMTS2.2GHz. This finding verifies the results in Figure 8,c.

4 Conclusions

A compact tuneable bandpass filter based on parallel line resonators has been designed and investigated. To extend the pass band frequency over a wide continuous range, a loading mechanism was used based on exploiting the varactor diode. The proposed design not only provided good band pass characteristics, but also demonstrates inherent attributes such as simple structure, lower complex, and reduced cost, realized over the entire tuning range. The proposed BPF occupies compact volume of \(0.12\lambda_0 \times 0.24\lambda_0 \times 0.007\lambda_0\), where \(\lambda_0\) is the wavelength of the lowest operating frequency. The results show that the proposed filter design provides some good characteristics fitting the need of the 4G cellular communications. Moreover, adjusting the present filter structure and substrate could make it capable to operate over the mmwave frequencies, which is considered as the potential spectrum for future 5G application. The substrate loss suppression is a crucial step towards the development and industrialization of high quality interconnects and passive elements. Filtering topologies based on GaN on SiC substrate could be foreseen as a promising candidate for the completion of the future 5G front-end chain. The design and development of compact GaN on SiC band-pass filter is envisaged to exhibit highly selective, high Q factor and low cost filter design. Also, with the aid of GaN on SiC substrate, such band pass filter will be easily and seamlessly integrated with the antenna and other RF front-end devices.

Acknowledgements

This work is carried out under the grant of the Fundação para a Ciência e a Tecnologia (FCT - Portugal), with the reference number: SFRH / BPD / 95110 / 2013. This work is supported by the European Union’s Horizon 2020 Research and Innovation program under grant agreement H2020-MSCA-ITN-2016-SECRET-722424.

References

[1] Y. Peng, L. Zhang, J. Fu, and Y. Wang, “Compact dual band bandpass filter using coupled lines multimode resonator”, Microwave Wireless Components Lett. vol. 25, no. 4, pp.235–237, (2015).

[2] G. Wu, L. Yang, and Q. Xu, “Miniaturised dual-band filter with high selectivity using split ring scheme”, Electron Lett. vol.51, Iss.7, pp.570–572, (2015).
[3] A. Boutejdar, A. Batmanov, M.H. Awida, E.P. Burte, and A. Omar, “Design of a new bandpass filter with sharp transition band using multilayer-technique and U-defected ground structure”, Microwaves Antennas Propagat IET, no.4, pp. 1415–1420, (2010).

[4] M.H. Al Sharkawy, D. Abd El-Aziz, and E. Galal, “A miniaturized low-/high-pass filter using double arrow head defected ground structure with centered etched ellipse”, Prog Electromagn Res Lett, vol.24, pp.99–107, (2011).

[5] L. C. TSAI, C. W. HSUE, “Dual-band bandpass filters using equal length coupled-serial-shunted line and Z-transform technique”, IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 4, p. 1111–1117, (2004).

[6] A. F. SHETA, “Narrow band compact non-degenerate dual-mode microstrip filter”. In Proceedings of the 25th National Radio Science Conference. Egypt, pp.1-7, (2008).

[7] D. J. Jung, J. N. Hansen, and K. Chang, “Piezoelectric transducer-controlled tunable hairpinbandpass filter,” IEEE Electronics Letters, Vol. 48, No. 8, pp. 440–441, (2012).

[8] M. Safari, C. Shafai, and L. Shafai, “X-band tunable frequency selective surface using MEMS capacitive loads,” IEEE Transactions on Antenna and Propagation, Vol., No. 99, pp.1–9, (2014).

[9] A. Ghalem, F. Ponchel, D. Remiens, and T. Lasri, “A 3.8 GHz tunable filter based on ferroelectric interdigitated capacitors,” IEEE International Symposium on the Applications of Ferroelectric and Workshop on the Piezoresponse Force Microscopy (ISAF/PFM), pp.252–256, Prague, (2013).

[10] N. Tentilier, F. Krasinski, R. Sauleau, B. Splingard, H. Lhermite, Ph. Coquet, “A liquid-crystal, tunable, ultra-thin Fabry-Perot resonator in Ka band”. IEEE Antennas Wirel. Propag. Lett. 8, pp.701–704 (2009).

[11] Y. Peng, T. Wang, W. Jiang, B.M. Farid Rahman, T. Xia, G. Wang, “Electrically tunable bandpass filter with patterned permalloy thin-film-enabled engineered substrate”. IEEE Trans. Magn., 51, pp.2006104-1–2006104-4 (2015).

[12] A.L. Borja, J. Carbonell, J.D. Martinez, V.E. Boria, D. Lippens, “A controllable bandwidth filter using varactor-loaded metamaterial-inspired transmission lines”. IEEE Antennas Wirel. Propag. Lett.10,pp. 1575–1578 (2011).

[13] J. X. Chen, Y. Ma, J. Cai, L.-H. Zhou, Z.-H. Bao, and W. Che, “Novel frequency-agile bandpass filter with wide tuning range and spurious suppression,” IEEE Trans. Ind. Electron., vol. 62, no. 10, pp. 6428–6435, (2015).

[14] H.-Y. Tsai, T.-Y. Huang, and R.-B. Wu, “Varactor-tuned compact dual-mode tunable filter with constant passband characteristics,” IEEE Trans. Compon., Packag., Manuf. Technol., vol. 6, no. 9, pp. 1399–1407, (2016).

[15] C. Liu, X. H. Wang, Y. Xu, and X.-W. Shi, “A Varactor-Tuned Bandpass Filter Using Open Split-Ring Resonators,” Progress In Electromagnetics Research Letters, Vol. 49, pp.99-104, (2014).

[16] HFSS version 14, Ansys Inc, USA, 2013, Available at:http://www.ansys.com/. Accessed on October 10, 2014.