Investigation of Compact Low Pass Filter with Sharp Cut–Off using Metamaterial

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Abstract. In this paper a new compact microstrip Bessel low pass filter (LPF) is experimentally validated using complementary split ring resonator (CSRR) which has sharper cut-off and improved spurious band suppression characteristics. The Richard's transformation and Kuroda's identities are used for realizing distributed Bessel LPF from the lumped element Bessel LPF. Traditionally Butterworth and Chebyshev LPFs are used in communication systems. Those LPFs exhibits high reflection in the pass-band and it is also very difficult to achieve sharper cut-off. Because of its poor cut-off and non linear phase characteristics, it will create cross talk between microwave systems. In order to overcome the above issues our proposed LPF which has linear phase and sharper cut-off behavior is an ideal subsystem in future microwave systems. Furthermore, to prove practical viability of the proposed design, a compact microstrip Bessel LPF was designed, simulated, fabricated and measured. It was observed from the experimentally compared results the proposed Bessel LPF with CSRR has better sharper cut-off characteristic than that without CSRR structure.

Keywords

Low-pass filter, spurious rejection, linear phase, complementary split ring resonators, resonators, microstrip filters, Bessel filter, microwave filters.

1. Introduction

High performance microwave and radio frequency (RF) filters are used in a wide spectrum of communication systems. The high performance is defined as the most efficient use of the costly spectrum, which leads to a very flat filter pass band and a steep transition into the rejection band while maintaining a small size and mass. The design of this type of filter is usually a trade- off between in-band insertion loss variations, out off-band isolation must be part of the trade-off and are purposefully omitted for simplicity, physical size and mass. Filter designers often find that very high quality factor (Q) is required in order to create high performance filters [1]. In order to increase the Q, one often must increase the size of the filter, resulting in a lar-

ger and heavier filter as well as it increases the insertion loss. Traditionally LPFs are used in the receiver system after the low noise amplifier (LNA) for interference filtering and signal channelization [2]. In order to access the modern microwave communication system requirements, compact microstrip LPFs with low insertion loss, sharp cut-off and wide stop-band are in high demand [3]. Normally LPFs are designed based on its frequency selective characteristics. This characteristic mainly depends on the Q value of the LPF. Depending upon the requirement such LPFs have Chebyshev and Butterworth type responses. However in several applications such as GBit/s digital signal transmission, video signal processing during the TV signal transmission, in WCDMA-UMTS mobile radio systems etc, nearly constant group delay response is required in order to avoid linear distortion and to maintain synchronization between transmitter and receiver [4]-[6]. The Bessel LPFs are suitable for such applications, even though these filters have slower cut-off [7]. The Bessel LPFs do not have only poor selectivity; their return loss in the pass band is also not satisfactory due to poor matching over the complete passband. The selectivity of the Bessel LPFs does not improve with increase in the order of the filter beyond five or six. The higher order Bessel LPF has only larger bandwidth for the constant group delay response [8]. However, it increases the design complexity and insertion loss. Another drawback is more variation in the theoretically calculated component values in the market. Hence their realization in lumped structure is problematic. However, lumped Bessel LPFs not only have large sizes but also have narrow stop-band and gradual cut-off frequency responses, which usually restrict their application ranges. Therefore compact, sharper cut-off and wide stopband planar LPFs are required [9]. Though increasing the order of the LPF can improve its performance; this enlarges the overall size and increases insertion loss [10]. In order to achieve a sharp cut-off frequency response, more sections are needed, but increasing sections will also increase the loss in the passband and circuit size [11]. In previous research, works focused only on defected ground structures (DGS) which are used for the same spurious band suppression. The applicability of DGSs for the given application can be converted either by EM simulation or by analysis through equivalent circuit model. The disadvantage of this method is that there is no direct correlation between the physical dimensions of DGS and the equivalent values of the L and C components. The derived performance of DGS is not fully predictable until the optimized solutions are achieved through trial and error process of continuous iteration [12]. Two filters with tapered dual-plane electromagnetic band gap structures (EBG) are proposed to achieve sharper cut-off; but these structures have low return loss in passband, very large size and narrow stopband [13]. In this paper, a simple compact microstrip Bessel LPF with CSRR is proposed and implemented. The proposed filter has low insertion loss, wide stopband, sharp cut-off and high harmonics suppression in the stopband. As compared with previous works [14], the proposed structure achieves better performance with sharper cut-off. The proposed filter has been designed, simulated, fabricated and measured. The measured results are in good agreement with the simulated results.

The structure of the paper is organized as follows: Section 2 explains the proposed LPF design. In Section 3, the experimental verification of the proposed filter is discussed. Simulation and measured results are presented in section 4. Section 5 concludes the paper.

2. Design of the Proposed LPF

2.1 Third-order Bessel LPF

The 3rd order lumped element Bessel LPF schematic diagram is shown in Fig. 1. Conventionally lumped filter requires larger area because the inductors have to be laid out sufficiently far from each other to avoid coupling [15].



Fig. 1. Schematic of Lumped Bessel LPF.

The third order Bessel response filter co-efficient values are calculated [16]. The Bessel LPF inductor and capacitor values are calculated [17] by using necessary impedance and frequency scaling and tabulated in Tab. 1.

| f _c (GHz) | $L_1(nH)$ | $C_2(pF)$ | $L_3(nH)$ |
|----------------------|-----------|-----------|-----------|
| 4 | 0.034695 | 0.192816 | 1.506879 |

Tab. 1. Calculated values of the Bessel LPF.

2.2 Distributed Bessel LPF

To accomplish the conversion from lumped to distributed element LPF; the Richard's and Kuroda's transformations are used. Richards's transformation allows us to replace lumped inductors with short circuit stubs and capacitors with open circuit stubs of characteristic impedance, Z_0 .

$$Z_0 = \frac{1}{C}, Z_0 = L.$$
 (1)

Kuroda's identities are used to realize an impractical value to practical values to achieve more suitable filter realization by performing any of the following operations: First physically separate transmission line stubs, second transform series stubs into shunt stubs, or vice versa and finally change the impractical characteristics impedances into more realizable one [18]. The distributed Bessel LPF is designed on the FR4 substrate with dielectric constant (ε_r) 4.5 and 1.6 mm thickness (*h*) as shown in Fig. 2. The design parameters are calculated from the microstrip line synthesis formula and values are given in Tab. 2.



Fig. 2. Layout of the distributed Bessel LPF without CSRR.

| Ζ (Ω) | Microstrip line Length (mm) | Microstrip line Width (mm) |
|-------|--------------------------------|-------------------------------|
| 50 | 10.08 | 2.97 |
| 59.4 | 5.12 | 2.18 |
| 50.9 | 5.05 | 2.88 |
| 87.9 | 5.31 | 0.91 |
| 116 | 5.45 | 0.38 |
| 206.4 | 5.78 | 0.008 |

Tab. 2. Design parameters of distributed Bessel LPF.

2.3 Design of the Proposed Bessel LPF with CSRR

The CSRR structures are designed and produced by applying the Babinet principle to the split ring resonators (SRR). In this way structures with apertures in metal surface are obtained and these CSRRs create negative ε instead of negative μ in a narrow range near the resonance frequency. In microstrip technology, left handed metamaterial structures exhibiting a band stop behavior can be implemented by etching CSRRs in the ground plane, underneath the conductor strip, and along the series capacitive gaps. The gap provides a negative value of the effective permeability up to certain frequency that depends on gap dimensions and separation. The negative ε structure has been obtained by loading a microstrip line with CSRR particles as shown in Fig. 3. There are many different parameters that affect resonance frequency of CSRR, most dominant being the permittivity of the substrate and length of the resonator. The resonance frequency is inversely proportional to the length of the resonator and is directly proportional to the split gap of the resonator. It is considered that the CSRR particle is etched only in the ground plane. CSRR etching depth decides the strength of the resonance increases [19]-[22].



Fig. 3. Microstrip loaded CSRR.

In order to improve the sharper cut-off, compact in size and harmonic suppression ability of the conventional Bessel LPF which one is not having CSRR, the CSRR structure is embedded in the ground plane of the conventional Bessel LPF. The CSRR is designed at the anti-resonance frequency. Inherent nature of anti-resonance behavior, it rejects the frequencies above cut-off frequency. In this way we achieved sharp cut-off. The layout of microstrip Bessel LPF with CSRR is shown in Fig. 4. The size of the CSRR inner ring radius r_1 = 4.179 mm, outer ring radius r_2 = 2.636 mm and gap g = 1.6 mm values are calculated from the cut-off frequency.



Fig. 4. Layout of the proposed Bessel LPF with CSRR.

3. Fabrication

The Bessel LPFs with CSRR and without CSRR structures are designed for the same design specification in order to evaluate their sharper cut-off and harmonic rejection ability behavior. Both the prototypes have been fabricated on FR-4 substrate. The photographs of the fabricated prototypes are shown in Fig. 5. The simulation was done in Agilent ADS software.



(a) Front side



(b) Back side Fig. 5. Fabricated prototype of Bessel LPF with CSRR.

4. Results and Discussion

The *S* parameter measurement of the fabricated prototypes has been carried out by using Agilent N5230A PNA series vector network analyzer. In order to verify the sharper cut-off and harmonic rejection ability of the proposed LPF's measured and simulated results are compared



Fig. 6. Return loss (S11).

with the LPF which one is not having CSRR. Fig. 6 and 7 show the return loss and insertion loss responses of the microstrip Bessel LPFs. It indicates the proposed Bessel LPF with CSRR has sharper cut-off ability than the Bessel LPF without CSRR structure. It clearly indicates that the proposed design rejects the higher order harmonics as well has maximally flat group delay in passband as well as stopband as shown in Fig. 8. The measured S parameter results are slightly different from simulated results because it includes connector losses and the absence of smooth transition between stubs. The overall performance comparison of the Bessel LPF is given in Tab. 3 and 4.



Fig. 7. Insertion loss (S_{12}) .



Fig. 8. Phase response (S_{21}) .

| Parameters | | Bessel LPF without CSRR | Bessel LPF with CSRR |
|-------------------------|-----------|----------------------------|-------------------------|
| | | f _c | f_c |
| S ₁₁ (dB) | Simulated | -4.52 | -1.583 |
| | Measured | -3.535 | -0.7074 |
| S ₁₂ (dB) | Simulated | -2.197 | -20.325 |
| | Measured | -2.992 | -21.3117 |
| S ₂₁ (phase) | Simulated | 42.013 | 28.65 |
| | Measured | 40.763 | 29.6 |

Tab. 1. Performance comparison.

| | Proposed Bessel LPF with CSRR | Bessel LPF without CSRR | [23] Butterworth | [23] Chebyshev |
|--|--|----------------------------------|---------------------|-------------------|
| Sharper cut-off deviation error | 0.1 | +3.8 | -1.2 | -1.7 |

Tab. 2. Performance comparison with existing LPF.

5. Conclusions

This paper concludes the Bessel LPF without CSRR design provides maximally flat group delay response in the passband. However, its sharpness of cut-off is very poor and impedance matching in the passband is also not satisfactory. In order to achieve sharper cut-off and harmonic rejection, the conventional LPFs need additional elements. Hence it increases the overall size and insertion loss of the microwave systems. Due to these limitations these LPFs are not popular in RF/microwave systems. Hence the proposed Bessel LPF with CSRR provides the constant group delay over a passband and rejects undesired frequencies without increasing the order of filter. In addition, it reduces the design complexity and cost. It is clearly observed that the proposed design can be used to design harmonics free with sharper cut-off wireless systems.

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