Australian Journal of Basic and Applied Sciences, 8(9) June 2014, Pages: 135-144

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

An Overview of Matched Bandstop Filters using Lossy Resonators

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ARTICLE INFO

Article history:
Received 2 March 2014
Received in revised form
13 May 2014
Accepted 28 May 2014
Available online 23 June 2014

Keywords:
matched bandstop filter, matched filter, absorptive filter, lossy resonator.

ABSTRACT

The overview of theory, design, development and application of matched bandstop filters using lossy resonators are presented in this paper. Theoretically, high notch depth and selectivity of matched bandstop filters can be produced by using only two lossy low Q resonators. Many matched bandstop filters have been developed during the last few years where the main targeted applications are advanced communication and electronic warfare systems. This article is mainly to provide the readers with some basic knowledge and insights about previous works of the matched bandstop filters using lossy resonators

To Cite This Article: N.A. Shairi, B.H. Ahmad, P.W. Wong, Z. Zakaria, An Overview of Matched Bandstop Filters using Lossy Resonators. ***Aust. J. Basic & Appl. Sci.**, 8(9): 135-144, 2014*

INTRODUCTION

Generally, the applications of microwave filters can be found such as in wireless base-stations (Mansour 2004), satellites (Fahmi *et al*. 2011) and wideband communication (Zakaria *et al*. 2013) where the bandstop filters would be most useful for isolating the signal of interest from interference signals (Naglich *et al*. 2010) (see Figure 1). The filter designs for system level perspective have been discussed by Hunter & Ranson (2007). They can be fixed filters (Hong & Lancaster 2001) or reconfigurable filters (Brito-Brito *et al*. 2011) that developed in planar (Hong & Lancaster 2002; Tang *et al*. 2011) or non-planar technologies (Wu 2012). Many general filter theories and design techniques can be found in text books (Hong & Lancaster 2001; David M. Pozar 2005; Hunter 2001; Makimoto & Yamashita 2001). Other advanced microwave filters design can be found in (Hunter & Abunjaileh 2008).

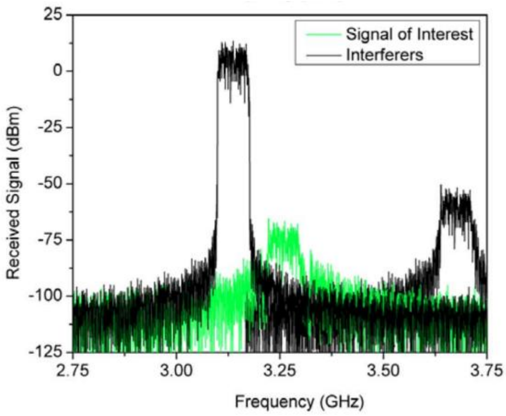

Fig. 1: Spectrum where a bandstop filter would be most useful for isolating the signal of interest (Naglich *et al*. 2010).

It is well known that the planar technologies particularly using microstrip is suffer from low Q factor compared with non-planar technologies such as coaxial and rectangular waveguide (Chang & Hsieh 2004;

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Zakaria *et al*. 2008). High notch depth and selectivity of matched bandstop filters is difficult to achieve with low Q factor of lossy resonator, unless multiple lossy resonators must be placed in the design for higher *n*-order of bandstop filter. However, it tends to be a physically large and complex.

In 2005, for the first time, Guyette *et al*. (2005) were successfully demonstrated an ideal infinite stopband attenuation of the matched bandstop where high notch depth and selectivity can be produced with only two lossy low-Q resonators in microstrip technology. The original idea was taken from Jachowski (2004) where it consists of two identical lossy resonators connected to the 90° hybrid coupler or directional coupler (Figure 2). This technique enables the use of low Q lossy resonators for high attenuation of bandstop filter applications. Thus, its advantages are not only to produce higher stopband attenuation but also to have matched at the input and output port of bandstop filter as well as compact in size.

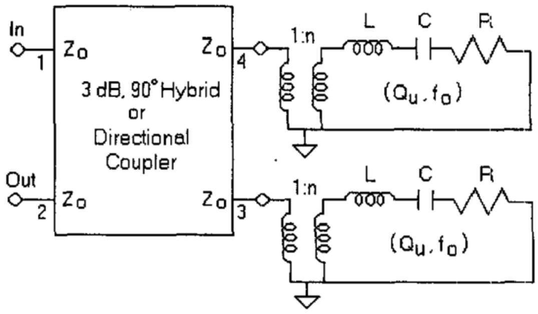

Fig. 2: Conceptual diagram of an enhanced-Q_u, notch filter employing a 3-dB, 90° hybrid coupler (Jachowski 2004).

Theory of Matched Bandstop Filter:

Matched bandstop filter has a characteristic of allpass network where an ideal lossless allpass network has the property of passing all frequencies with zero attenuation, and thus must present a perfect match at all frequencies (Guyette *et al*. 2009). As explained by Jachowski (2005), when a second-order bandpass filter is connected in parallel with an all-pass phase shift element (shown in Figure 3), a particularly compact form of absorptive bandstop filter can be realized. Figure 4 shows a generalized model of matched bandstop filter using lossy resonator.

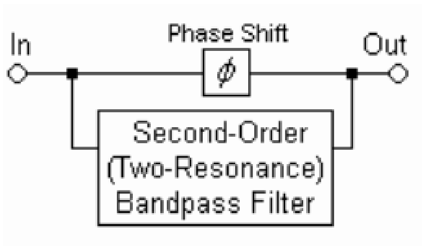

Fig. 3: Conceptual diagrams of first-order absorptive bandstop filters based on a single second-order bandpass filter (Jachowski 2005).

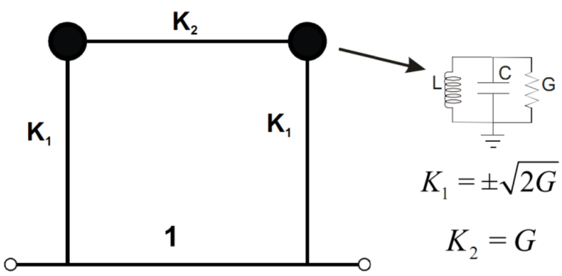

Fig. 4: Generalized model of matched bandstop filter using lossy resonator (Guyette *et al*. 2005).

The theory of matched bandstop filter using lossy resonator is derived from allpass network (Guyette *et al*. 2005; Hunter *et al*. 2005). Consider an even-mode and odd-mode analysis of matched bandstop filter, a transfer matrix of the symmetrical network is given by

$$[T_R] = \begin{bmatrix} \left(\frac{Y_e - Y_o}{Y_o - Y_e}\right) & \left(\frac{2}{Y_o - Y_e}\right) \\ \left(\frac{2Y_eY_o}{Y_o - Y_e}\right) & \left(\frac{Y_e - Y_o}{Y_o - Y_e}\right) \end{bmatrix} \quad (1)$$

where Y_e is even-mode and Y_o is odd-mode of admittance of the resonator. Converting the transfer matrix in (1) to *S*-parameter, we get

$$S_{11} = S_{22} = \frac{1 - Y_eY_o}{(Y_o + 1)(Y_e + 1)} \quad (2)$$

and

$$S_{21} = S_{12} = \frac{Y_o - Y_e}{(Y_o + 1)(Y_e + 1)} \quad (3)$$

If $Y_o = \frac{1}{Y_e}$, then

$$S_{11} = S_{22} = \frac{1 - Y_e\left(\frac{1}{Y_e}\right)}{\left(\frac{1}{Y_e} + 1\right)(Y_e + 1)} \quad (4)$$

$$= \frac{1 - 1}{\left(\frac{1}{Y_e} + 1\right)(Y_e + 1)} \quad (5)$$

$$= 0$$

which is a perfectly matched at all frequencies and the network possesses the allpass property.

If $Y_o = Y_e$ at a certain frequency, then

$$S_{21} = S_{12} = \frac{Y_e - Y_e}{(Y_e + 1)(Y_e + 1)} \quad (6)$$

$$= \frac{0}{(Y_e + 1)^2} \quad (7)$$

$$= 0$$

which is an infinite attenuation or notch can be obtained at that frequency. By considering Y_e as a lossy circuit as shown in Figure 5, then

$$Y_e = R + j\omega L + \frac{1}{j\omega C} \ . \quad (8)$$

where it can be used for further analyzing of any lossy resonator in matched bandstop filter.

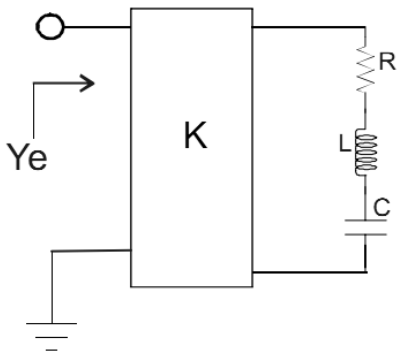

Fig. 5: Even-mode admittance of a lossy resonant circuit (Guyette *et al*. 2005).

As stated by Hunter *et al*. (2005), both the all-pass (perfectly matched) and the perfect notch property are met when $K_1 = \pm\sqrt{2G}$ and $K_2 = G$. It can be done by matching the source or load resistance into the resonator resistances at stopband frequencies, so that signal power is dissipated in, rather than reflected from, the lossy resonators (Jachowski 2006).

Other conceptual of matched bandstop filter can be found in (Jachowski 2004; Jachowski 2005). The author proposed matched bandstop filter using two first-order bandpass filters (see Figure 6) and the more complex circuit such as distributed bridged-T notch filter and triple-mode-resonator notch filter. The main disadvantage of these topologies is larger in cicuit size compared with topology in Figure 3. Besides, a new topology of cascadable matched bandstop filter for wider bandwidth was proposed by Jachowski (2006).

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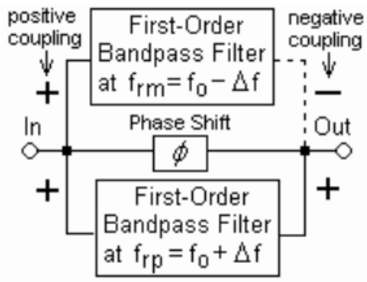
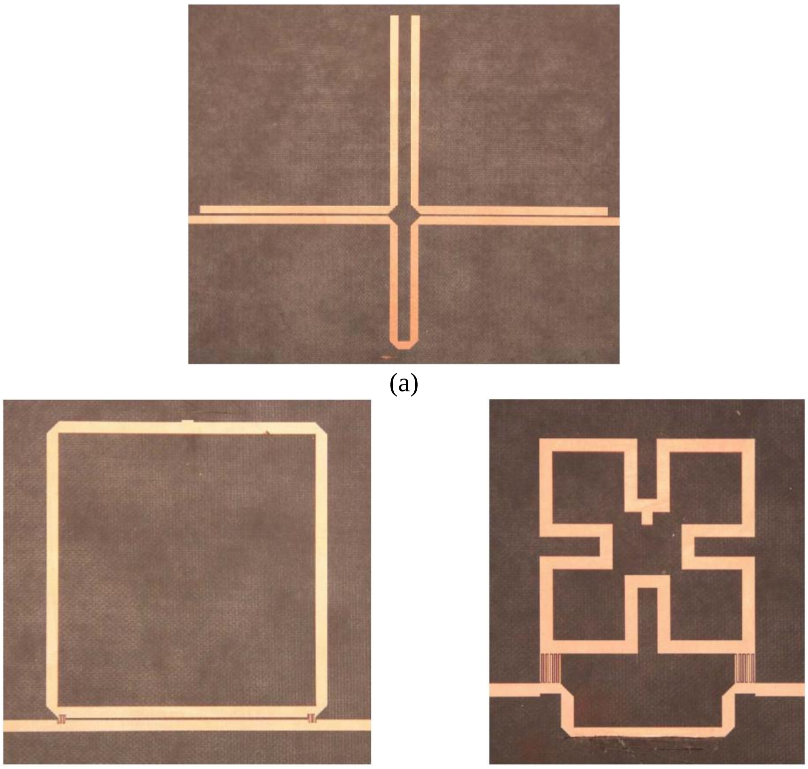


Fig. 6: Conceptual diagrams of matched bandstop filter using two first-order bandpass filters (Jachowski 2005).

Realization of Matched Bandstop Filter:

Figure 7 shows the prototypes of matched bandstop filter that first demonstrated by Guyette *et al*. (2005). It was realized in different types of distributed element of lossy resonators which are parallel-coupled half wave length resonator (Figure 7(a)), ring resonator (Figure 7(b)) and folded ring resonator (Figure 7(c)) giving the unloaded Q of 159, 208 and 168 respectively. All the prototypes were fabricated on Rogers Duroid 5880 with a ε_r of 2.2, a substrate thickness of 0.787 mm, and a metal thickness of 24 µm.



(a)

(b) (c)

Fig. 7: First experimental realization of matched bandstop filter using lossy resonators in microstrip technology (Guyette *et al*. 2005); (a) parallel-coupled half-wavelength resonator, (b) ring resonator and (c) folded ring resonator.

After the first prototypes from Guyette *et al*. (2005), other distributed element of lossy resonators or different shapes of matched bandstop filters have been proposed and reported by other researchers (Guyette *et al*. 2009; Wong *et al*. 2007; Jachowski & Guyette 2009; Guyette 2010; Adoum & Wong 2011a; Guyette 2012). Besides, the matched bandstop filter was also realized by using lumped element type of resonator (Jachowski 2010; Lee *et al*. 2012). They were designed for different targeted applications or with improvement of the previous designs. The details of the designs are explained in the next paragraphs.

Depicted in Figure 8 is a matched bandstop filter comprising T-shunt stub and varactor diode fabricated on Rogers Duroid 5880 (Wong *et al*. 2007). The varactor diode was used to tune the impedance inverter of T-shunt stub for different attenuation responses. It was demonstrated at frequency of 983.6 MHz with the loaded Q of 76.

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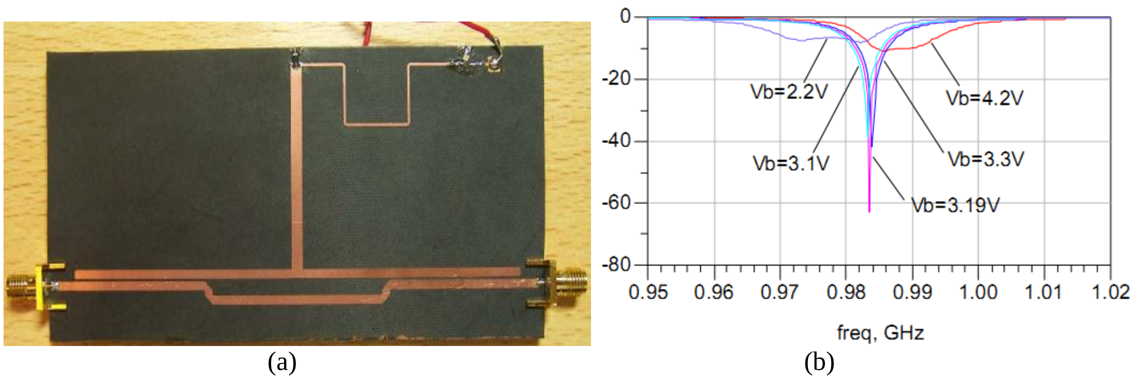


Fig. 8: (a) Matched bandstop filter with T-shunt stub and varactor diode and (b) transmission response (S_{21}) with varactor bias (V_b) tuning from 2.2V to 4.2V (Wong *et al*. 2007).

As shown in Figure 9, a parallel-cascaded matched bandstop filter comprising dual mode ring resonators that fabricated on Rogers RT Duroid 6010 was proposed by Guyette *et al*. (2009). It was designed at 1.873 GHz to provide high selectivity of bandstop filter utilizing predistorted allpass networks technique (a trade-off between selectivity and passband insertion loss). Thus, the measured passband insertion loss is 7.2 dB and the 3-dB bandwidth is 179 MHz.

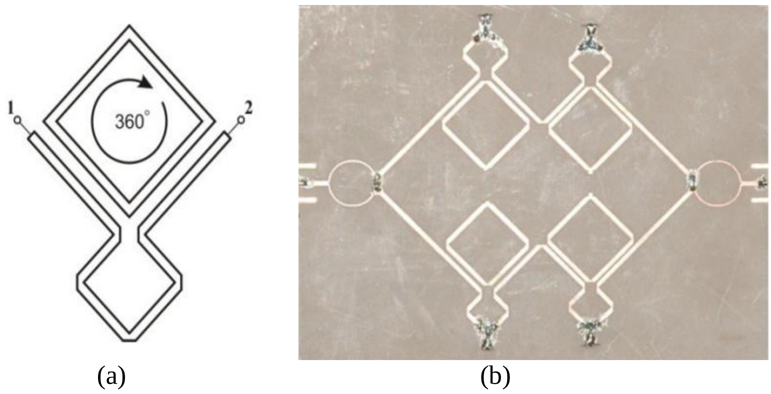


Fig. 9: (a) Matched bandstop filter using dual mode ring resonators and (b) prototype of cascaded parallel-cascaded matched bandstop filter (Guyette *et al*. 2009).

A design shown in Figure 10 is the proposed tunable absorptive notch filter based on edge-coupled λ/2 resonators that was reported by Jachowski & Guyette (2009). By utilizing edge-coupled resonators, the matched bandstop filter was designed to provide constant bandwidth response when tuning at different frequencies. Varactor diodes were used for the tuning and the design was fabricated on Rogers RO3210.

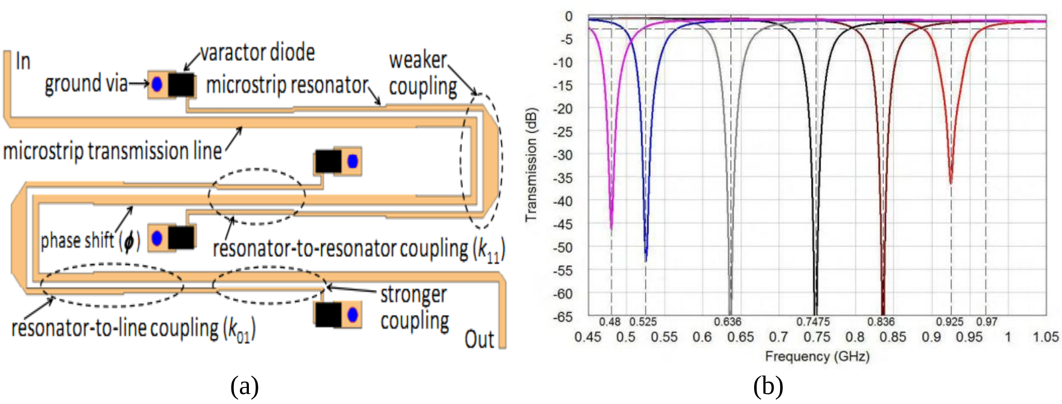


Fig. 10: (a) Single-stage matched bandstop filter using edge-coupled λ/2 resonators and (b) transmission response (S_{21}) with different tuning voltages (Jachowski & Guyette 2009).

A tunable 2nd-order absorptive bandstop filter with both center frequency and bandwidth tuning was proposed by Guyette (2010) (see Figure 11). The resonators are coupled to a transmission line twice where the bandwidth is determined not only from the strength of the couplings but also from the electrical length of the associated through line. It was fabricated on Rogers Duroid RO4003 and by employing varactor diodes, the bandwidth tuning is controlled by differentially two varactors attached at opposite ends of the resonator, and the center frequency tuning is controlled by tuning both varactors simultaneously. The center frequency can be tuned from 1.2 GHz to 1.6 GHz while the bandwidth can be tuned from 70 MHz to 140 MHz.

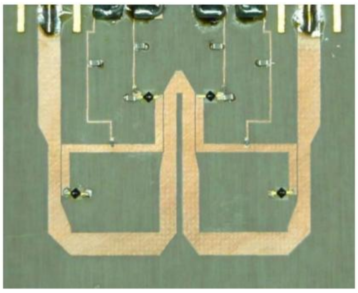
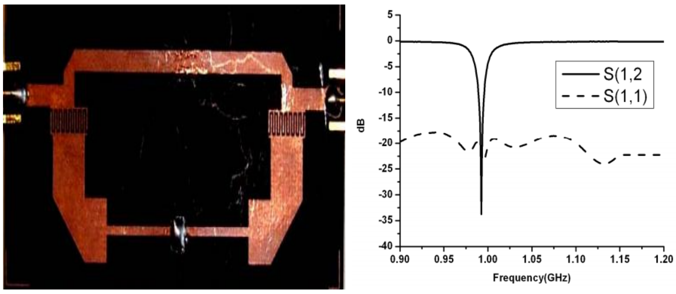


Fig. 11: 2nd-order matched bandstop filter using lossy resonators coupled to a transmission line twice (Guyette 2010).

Stepped impedance resonator (SIR) has a characteristic of smaller size compared with other distributed element of microstrip line resonators. Therefore, as depicted in Figure 12, a matched bandstop filter using SIR for compact size was proposed by Adoum & Wong (2011a). It was fabricated on Roger RT Duroid 5880 and operating at 0.99 GHz. Besides, the proposed miniaturized matched band-stop filter was able to achieve high stopband attenuation even with low Q factor values and the first spurious resonance frequency due to short length occurs at 4.7 times the fundamental resonance frequency.



(a) (b)

Fig. 12: (a) SIRs for compact size of matched bandstop filter and (b) transmission response (S_{21}) and return loss (S_{11}) (Adoum & Wong 2011a).

As proposed by Guyette (2012), Figure 13 is two intrinsically switched bandstop sections in cascade, with a small amount of coupling introduced between the two coupled-line resonators, thus significantly producing a matched bandstop filter. The design has a second-order notch response with more than 50 dB of rejection continuously tunable from 665 to 1000 MHz (50%) with negligible passband ripple in the intrinsic off state. It was fabricated on Rogers Duroid 4003.

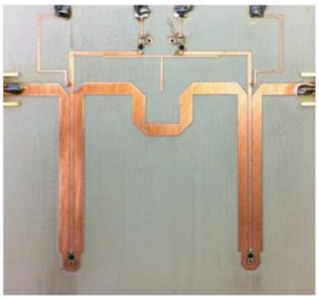


Fig. 13: Intrinsically switched tunable matched bandstop filter (Guyette 2012).

An absorptive bandstop filter topology using LTCC technology was proposed by Lee *et al*. (2012). As shown in Figure 14, it capables of creating large attenuation using low-small-size resonators. It was fabricated on LTCC substrate with lumped elements such as chip capacitors where the entire size is 2.7 x 2.2 x 0.7 mm^3. Thus, compared with the microstrip matched bandstop filters in Figure 7 to 13, the proposed structure in (Lee *et al*. 2012) is smaller in size because there is no quarter wavelength transmission line between two resonators and the resonators are lumped elements. However, the design is complicated due to its multi-layer structure.

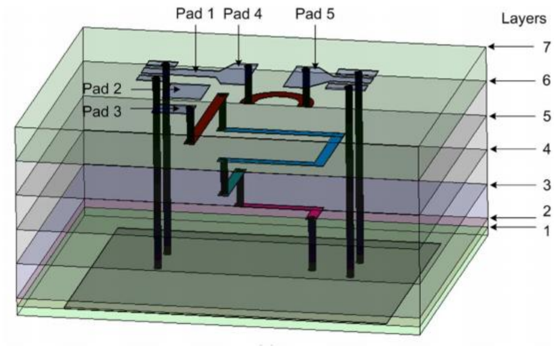


Fig. 14: 3-D view of the proposed matched bandstop filter structure using LTCC technology (Lee *et al*. 2012).

Design Challenges of Matched Bandstop Filter:

As reported by Guyette *et al*. (2005) and Jachowski (2005), in the post-fabrication of matched bandstop filter, the circuits were tuned using dielectric overlays and/or selectively removing metallization in order to obtain the maximum attenuation or notch, particularly at the parallel line resonators to transmission microstrip line couplings. The same approach can also be found in other works (Jachowski & Guyette 2009; Zahari *et al*. 2011). Certain manual-optimization approaches were reported by Jachowski & Rauscher (2009) and Jachowski & Alexandaria (2012) that require iterative-analysis between simulation and measurement process of the couplings and other circuit parameters.

As investigated by Zahari *et al*. (2012), the key problem in the couplings of parallel line resonators to transmission microstrip line is the variation or tolerance of coupling gap during the fabrication process that cause a slightly different response between measured results and simulated results. It is found that the attenuation (or bandstop response) is very sensitive to the gap size of the coupled line. The smallest changes of coupling gap will change the attenuation level.

Applications of Matched Bandstop Filter:

In general, most of papers regarding matched bandstop filter are primarily focused on application of RF interference rejection or attenuation in RF front-end system design (Hunter *et al*. 2005; Phudpong & Hunter 2007; Jachowski 2010). Hunter *et al*. (2005) discussed challenges of RF receiver design in dealing with bandpass and bandstop filter such as circuit size versus filter performance, cost versus filter design technology and effect of filter performance to the RF receiver performance (e.g. noise figure and third order intermodulation distortion). Therefore, the authors suggested several new solutions either using predistorted reflection mode filter, predistorted transmission mode filter or matched bandstop filter.

Started from 2007, the matched bandstop filter based on the circuit topology in Figure 2 is the first reported by Phudpong & Hunter (2007) for application of Frequency Selective Limiting (FSL) in RF receiver system. The design is based on the reflection mode configuration (Jachowski 2004) to provide a perfect notched response and has a variable attenuation level controlled by Schottky diodes. It was successfully demonstrated at 2 GHz with indicate 0 dBm limiting threshold, 32 dB limiting level, 2 dB insertion loss and 200 MHz limiting bandwidth. The other similar applications were reported by Jachowski & Rauscher (2009) and Jachowski & Alexandaria (2012) which are based on the previous design in Figure 7(a) (Jachowski 2005; Guyette *et al*. 2005). The targeted application is for receiver systems that have a flexibility to change attenuation level and frequency of bandstop filter for rejecting different level and different frequency of interference signals simultaneously. It was fabricated on Rogers RO4003 and successfully demonstrated a stopband attenuation from 30 dB to 50 dB and the operating frequency is from 1.8 GHz to 2.2 GHz.

Jachowski & Guyette (2010) reported the recent development of filter technology from Naval Research Laboratory, United State of America. The application of fixed frequency filter, tunable filter and attenuator for spectrum management was discussed. As mentioned in the report, matched bandstop filter is one of the good candidates for advanced communications and electronic warfare systems. In fixed frequency filter, it can be used to attenuate known interferers at a receivers input and to prevent transmitters from broadcasting interference within sensitive frequency bands. In tunable filter and attenuator, it can be effectively used in adaptive communication system that uses multi-channel or multi-band communication.

Multiple fixed bandstop filters for the purpose of multiple known interference suppression are required in communication systems. Therefore, Hamzah *et al*. (2010) successfully demonstrated the proposed design from Guyette *et al*. (2005) for multiband matched bandstop filter. It was designed using FR4 substrate and attenuated at frequency of 1 GHz and 2 GHz. The same effort was done by Adoum & Wong (2011b) and Adoum & Wong (2012a) for smaller size of multiband matched bandstop filter using stepped impedance resonators. It was fabricated on Roger RT/Duroid 5880 and attenuated at frequency of 0.99 GHz and 1.04 GHz.

Reconfigurable matched bandstop filters were designed and proposed for solution of adaptive communication systems (Zahari *et al*. 2011; Zahari *et al*. 2012; Adoum & Wong 2012b; Adoum & Wong 2013). The designs can be switched between bandstop and allpass response allowing a flexibility in RF front-end design to attenuate interference signals. The designs from Zahari *et al*. (2011) and Zahari *et al*. (2012) are based on matched bandstop filters from the designs in Figure 7(a) and (b) (Guyette *et al*. 2005) while the designs from Adoum & Wong (2012b) and Adoum & Wong (2013) are based on their previous design as shown in Figure 12(a) (Adoum & Wong 2011a). Besides, the reconfigurable matched bandstop filter that proposed by Zahari *et al*. (2011) was applied in RF switch design for TD-SCDMA at 2.010 - 2.025 GHz (Shairi *et al*. 2012) and Time Division Duplex switching in 3 GHz band (Shairi *et al*. 2014).

Conclusion:

In this paper, the theory, design, development and application of matched bandstop filters using lossy resonators have been reported. The theory of matched bandstop filters using lossy resonator is derived from allpass network by considering an even-mode and odd-mode analysis. Most of the matched bandstop filters are realized in microstrip technology in order to obtain high Q of microstrip bandstop filters where theoretically infinite attenuation can be produced by using only two lossy low Q resonators. However, there is a design challenge of couplings of parallel line resonators to transmission microstrip line where it requires tuning or manual-optimization in post-fabrication to optimize the attenuation or notch performance. Most of the application of these bandstop filters can be found in advanced communications and electronic warfare systems. They are used for RF interference rejection or attenuation in RF front-end system design. In these applications, the matched bandstop filters can be fixed frequency filters, tunable filters, attenuators and RF switches.

ACKNOWLEDGEMENT

We would like to acknowledge the contribution of our colleagues from Faculty of Electronics and Computer Engineering, UTeM for this manuscript preparation. The publication of this work is funded by Fundamental Research Grant Scheme (FRGS), Ministry of Higher Education, Malaysia (project number FRGS/2012/ FKEKK/TK02/03/2/F00128).

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