Designing of Hairpin-Line Band Pass filters for DCS, UMTS and LTE-Systems

Muhammad Sayidi, Mudrik Alaydrus
Universitas Mercu Buana, Jakarta

Abstract

Bandpass filters are essential components in any wireless systems. They are designed for selecting desired signal from other signals. Especially in crowded frequency spectrums, accurate filter characteristics are required to guarantee the performance of the overall systems. DCS, UMTS and LTE systems are the actual communication systems used by hundred million users. Bandpass filters designed here is based on hairpin line structures and implemented in microstrip technology. The filters are five order Chebychev's bandpass filters. The center frequency of each system determines the total length of the U-form hairpin structure. The design starts with exploiting the coupling between the resonators. The coupling between two adjacent resonators is determined by the fractional bandwidth of the system and the element value derived from the Chebychev's approximation. The value of the coupling factor leads to the distance between two adjacent resonators. The simulation results conform to the specifications given in the standards. In general, the measurements verify the simulation. We see worse reflection factors and more insertion loss eventually due to bad soldering of the connectors to the filters. The shifting and width of the pass regions are also observed, which are probably due to the finite accuracy in prototyping the filters.

Keywords: *bandpass filter, coupled filters, DCS, hairpin, LTE, UMTS.*

Received August 2015
Accepted for Publication November 2015

1. INTRODUCTION

The need for more capacity and high data rate leads to the introduction of new wireless systems in already crowded frequency spectrum. The management of the spectrum plays a significant role to control any unwanted interferences. From the view of point in physical layer, bandpass filters are designed for this purpose. Bandpass filters pass desired signals from other unwanted signals [1]. To get sharp filtering characteristics, in traditional filter approximations, such as Butterworth and Chebychev realizations, we need many resonators, which leads to big filter dimensions. The introduction of transmission zeros enhances the selectivity near the pass band [2].

Lee et al [3] designed a bandpass filter for IMT-2000 around 2 GHz, they used a simple square open-loop resonator as based for building the filter. An other resonator structure is proposed by [4], a novel bandpass filter with sharp attenuations and wide stopband is developed through the combined use of composite resonators and stepped impedance resonators (SIRs). Parallel coupled bandpass filters are developed for several frequency regions, such as around 5.75 GHz [5], and around 5 GHz [6].

In this work, three bandpass filters for Digital Cellular Service (DCS 1800), Universal Mobile Telecommunications System (UMTS 2100) and Long Term Evolution (LTE) are designed. The detailed frequency bands for these systems are: The DCS 1800 band spans in interval 1710.2 – 1784.8 MHz (uplink) and 1805.2 – 1879.8 MHz (downlink) [7], the UMTS frequency band used here is the operating band 1 (used in Asia region), with the intervals 1920 – 1980 MHz (uplink) and 2110 – 2170 MHz (downlink) [8] and the LTE system described here uses the operating band 7, 2500 – 2570 MHz (uplink) and 2620 – 2690 MHz (downlink). This information is important for design question, which gives the center frequency and fractional bandwidth (FBW) for each system. The center frequency in the mid frequency between uplink and downlink bands, whereas the fractional bandwidth is the ratio between the total bandwidth and the center frequency. The center frequency gives a direct impact to the dimension of the hairpin filter as designed in [10]. In this work we would like to make a replica of the design by different material and fabricate it to do measurement for verification of the design. Whereas the fractional bandwidth and the element values of the equivalent low pass filter correlate with the coupling factors between two adjacent resonators.

2. DESIGNING OF BANDPASS FILTERS

2.1 Low Pass Filter with Chebychev's Response

The design of bandpass filter begin with designing the low pass filter prototype. As designed in [10], here all designed filters are also approximated by an equivalent Chebychev-based low pass filter with order N = 5 and passband ripple of L_{Ar} = 0.1 dB, which from table 3.2 in [11] leads to the following element values

$$g_0 = g_6 = 1.0,$$
$$g_1 = g_5 = 1.1468,$$
$$g_2 = g_4 = 1.3712 \text{ and}$$
$$g_3 = 1.975.$$

The choice of the order of the filter and the passband ripple here is rather arbitrary. It is more to the trade-off between the filter selectivity and the dimension of the filter.

2.2 Hairpin-Line Band Pass Filter in Microstrip

In this work, the bandpass filters are implemented in a TMM10 substrate [12] with a relative permittivity of 9.56, tangent loss of 0.0022 and a thickness of 0.635 mm.

The hairpin filter has a U-form strip, which is chosen here of 1.0 mm width. The total length of the U-structure is about a half of the guided wavelength, which by given frequency, substrate information can be calculated [13], and given in table 1.

TABLE I Center frequency, fractional bandwidth and guided Wavelength of DCS, UMTS and LTE Systems

Application	DCS	UMTS	LTE
Center frequency [MHz]	1795	2045	2595
Fractional bandwidth	9.5%	12.2%	7.3%
Rel. effective permittivity	6.75	6.76	6.78
Guided wavelength [mm]	64.4	56.5	44.4

The fractional bandwidth (*FBW*) is given in table 1 for designed purpose. Fig. 1 gives dimensions of the hairpin form to be used in the next section. These are structures which are able to resonate at their center frequency. In order to enhance the selectivity of the filters, several such resonators are arranged close to each other.

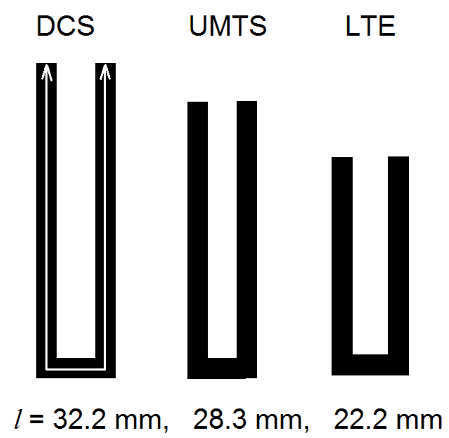

Fig. 1. Dimension of the hairpin form for each system.

Two closely arranged resonators interact to each other and build a coupling between them, which is described quantitatively by a coupling factor. In [11], the coupling factor between resonator *j* and resonator *k* can be calculated by

$$k_{jk} = FBW/\sqrt{g_j g_k} \tag{1}$$

Table II summarizes the coupling factors for all systems under consideration. The table reveals, that due to the symmetry we need just to analyze two couplings for each system.

TABLE II Coupling factor between the resonators.

Coupling factor between resonator	DCS	UMTS	LTE
1-2	0.0758	0.0957	0.0558
2-3	0.0577	0.0729	0.0425
3-4	0.0577	0.0729	0.0425
4-5	0.0758	0.0957	0.0558

2.3 Calculation of Coupling Factor

The coupling factor represents how big two resonator are coupled to each other. In order to get the coupling factor numerically, a model as illustrated in Fig.2 left side, is simulated by the software Sonnet v.15 [14].

Two resonators are closely arranged in alternate form and fed loosely to input and output ports. The software Sonnet can calculate the transmission factor (S_{21}). From the physics of the structure, if the resonators are removed away from each other, each resonator works alone, and it exists just a resonant frequency.

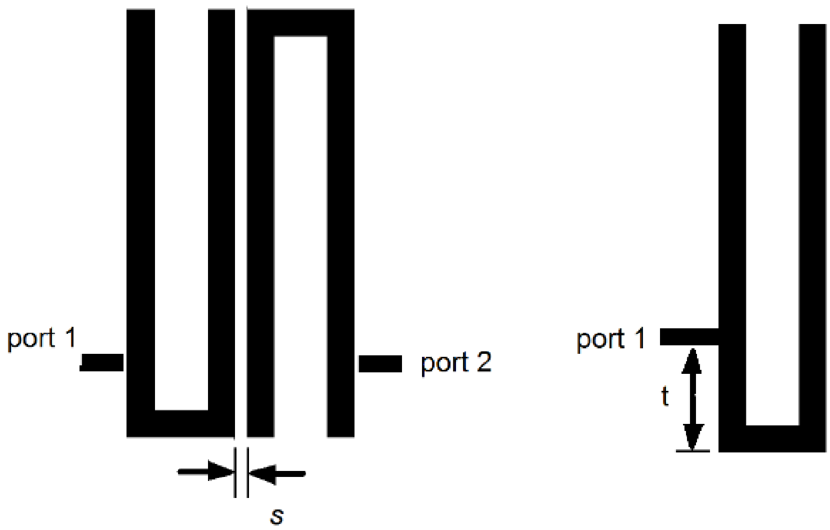

Fig. 2. Left: Coupling of two closely arranged resonators, right: feeding external coupling into the filter

If the distance s is small enough, the resonators interact to each other, we find two resonances in the transmission factor. The coupling factor can be calculated by

$$k = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \qquad (2)$$

f_1 and f_2 are the resonant frequencies.

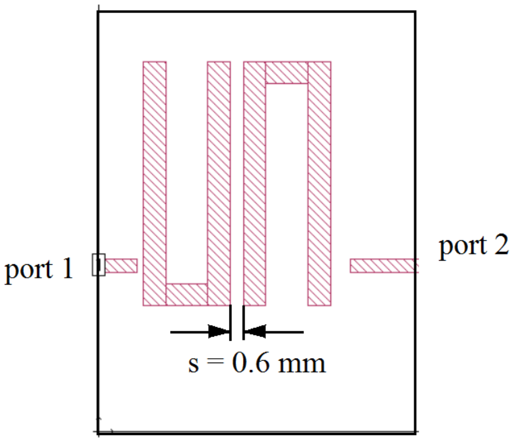

Fig. 3 The LTE-Filter structure for coupling calculation

Fig. 3 shows the filter structure for coupling calculation. The resonator structure to be observed is arranged, the resonators are located separated at certain distance to analyze the coupling effect between them. It is clear from the physical logic, if the resonators are very close to each other, they are coupled very strong, and if the resonators are arranged in large distance, they are coupled very weak, and maybe there is no coupling between them. The resonator structure is loose fed by input and output ports.

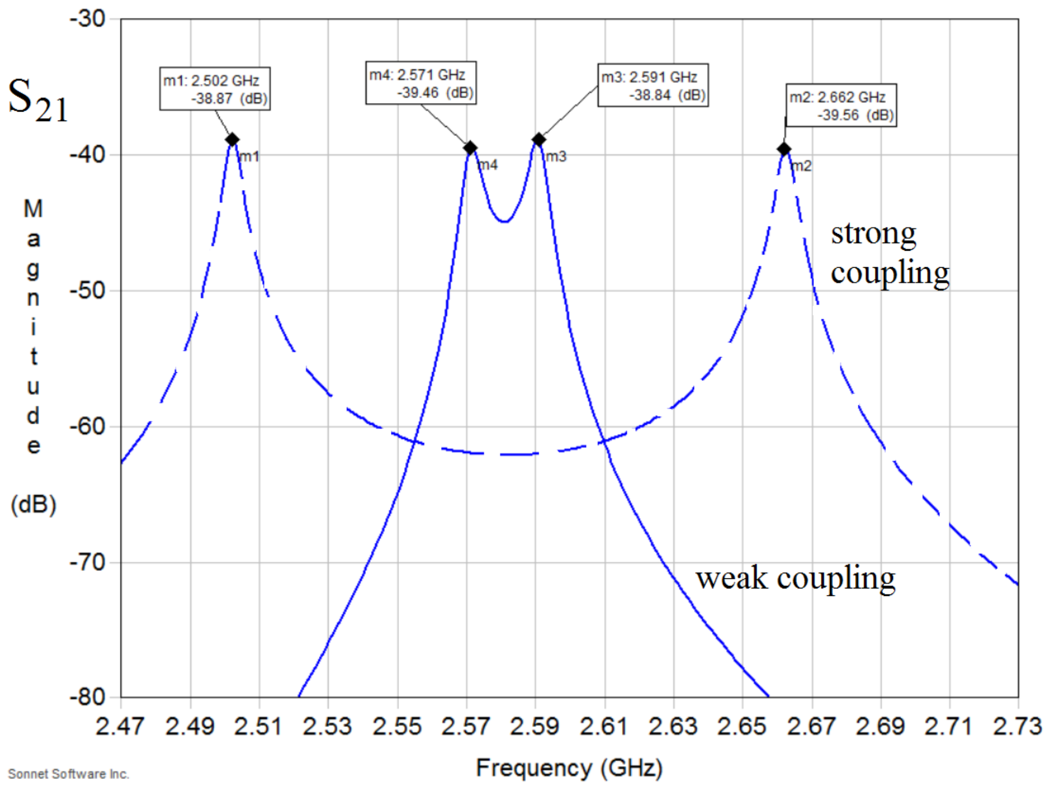

Fig. 4 The transmission factor S_{21} of resonator structure in Fig. 3 at s=0.6 mm for strong coupling and at s=2.3 mm for weak coupling.

Through numerical calculation by Sonnet, we get the transmission factor S_{21}, whose magnitude is depicted in Fig. 4. By extracting the resonant positions (the peak), we get for each resonator separation two resonant frequencies for coupling calculation. We see, if the resonant frequencies are far from each other, due to eq. (2) we can get big coupling factor, which means strong coupling. Whereas if the resonant frequencies are close to each other, we obtain small coupling factor, which indicates weak coupling.

In order to distinguish the type of the coupling, whether electric or magnetic, we have to observe the phase of the transmission factor of the structure at each distance. Fig. 5 shows the phase for s=0.6 mm and 2.3 mm. We see, for the frequency interval between the peaks, the phase is smaller than outside the interval. It indicates that for both distances there exists electric coupling.

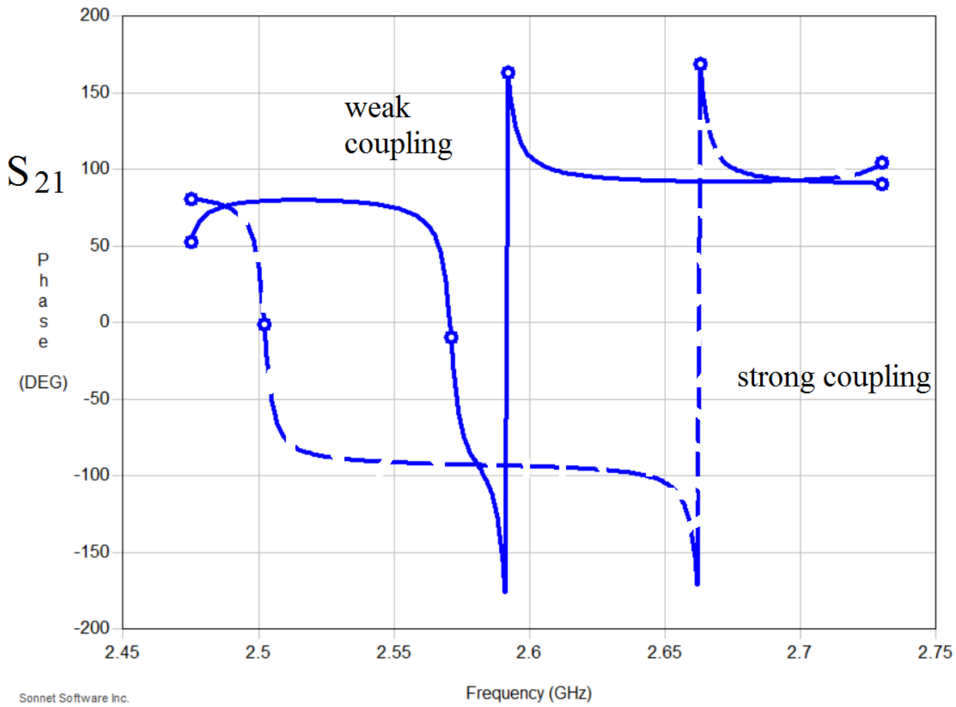

Fig. 5 The phase of transmission factor S_{21} of resonator structure in Fig. 3 at s=0.6 mm for strong coupling and at s=2.3 mm for weak coupling.

By varying the distance *s* we can get the coupling factor as function of the distance as shown in Fig. 6. Based on these curves, we can extract the distance *s* to gain certain coupling factor.

For the DCS system, a coupling factor of k_{12} = 0.0758 can be achieved by setting the distance *s* = 0.5 mm between the first and second resonator, whereas a smaller coupling factor k_{23}=0.0577 is gained by setting a larger distance of *s* = 0.7 mm.

For the UMTS systems, a larger coupling factor of k_{12} = 0.0957 is achieved by the distance *s* = 0.35 mm between the first and second resonator. For the simulation this number is replaced by 0.40 mm, because accuracy of 0.05 mm would double the memory needs for the calculation. The coupling factor k_{23}=0.0729 can be gained by setting a larger distance of *s* = 0.5 mm.

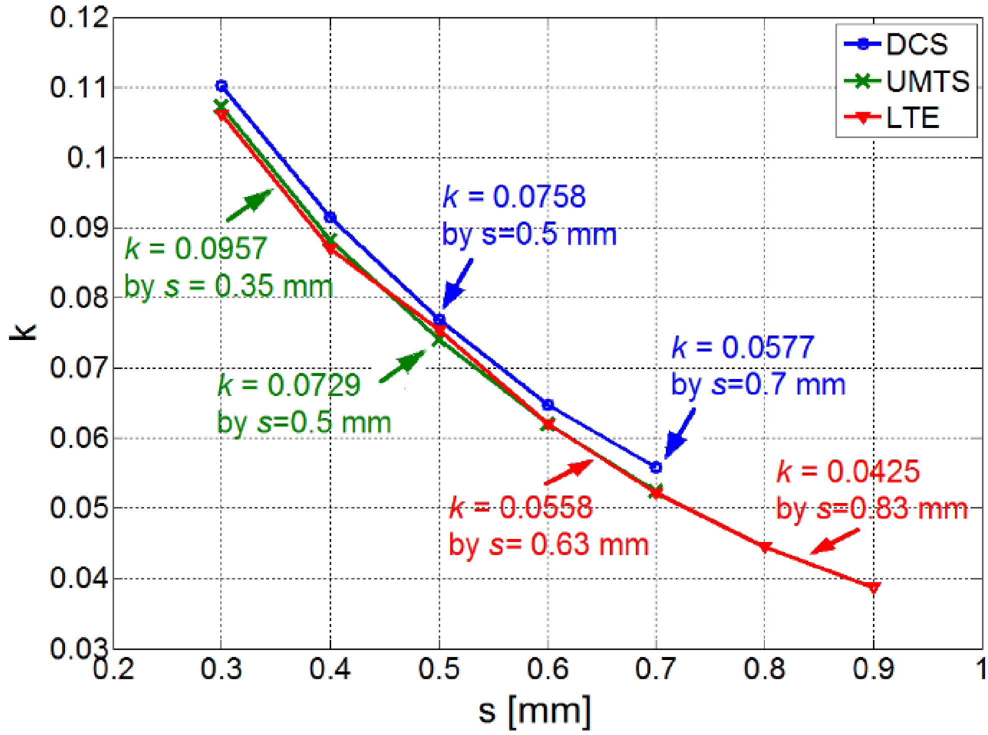

Fig. 6. Coupling factor as function of distance *s*.

For designing the LTE system, a coupling factor of k_{12} = 0.0558 can be obtained by setting the distance s = 0.63 mm, which is approximated by 0.6 mm. The coupling between the second and third resonator k_{23}=0.0425 is realized by a larger distance of s = 0.83 mm, which approximated by 0.8 mm.

2.4 Calculation of External Quality Factor

Besides the coupling factor, another important number is the external quality factor. The external quality factor describes the quality of the feeding of input and output ports to the internal side of the filter. The external quality factor, as given in [hong], can be calculated by

$$Q_{ei} = g_o g_1 / FBW \text{ and} \quad (3)$$

$$Q_{eo} = g_5 g_6 / FBW \quad (4)$$

With the data in section 2.1. the external quality factors for DCS, UMTS and LTE are 12.07, 9.56 and 16.38, respectively.

A model for numerical calculation the external quality factor is shown in Fig. 2 right side. The model uses just a port, so that for the calculation just the reflection factor is important, by using the phase of the reflection factor, the external quality factor can be calculated by

$$Q_e = f_0 / (f_{90} - f_{-90}) \quad (5)$$

f_0, f_{90} and f_{-90} are the frequencies for the phase $\measuredangle S_{11} = 0^o$, 90^o and -90^o respectively. Which can be extracted by the reflection factor from any numerical calculation.

Fig. 7 gives the LTE-filter structure for calculating the external quality factor. Here, we use just a port.

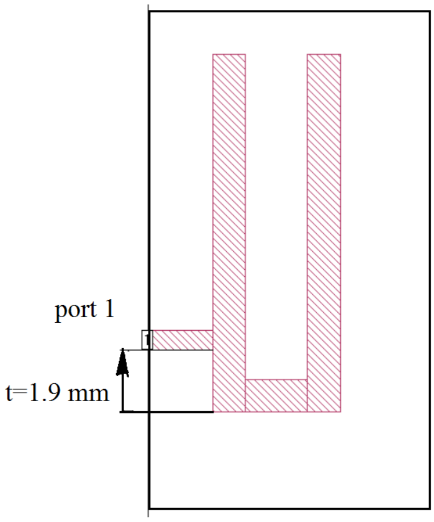

Fig. 7 The LTE-Filter structure for calculation of external quality factor

The result of the calculation of the structure in Fig. 7 is depicted in Fig. 8. We can position the frequencies for the phases needed for calculation of the external quality factor in eq. (5).

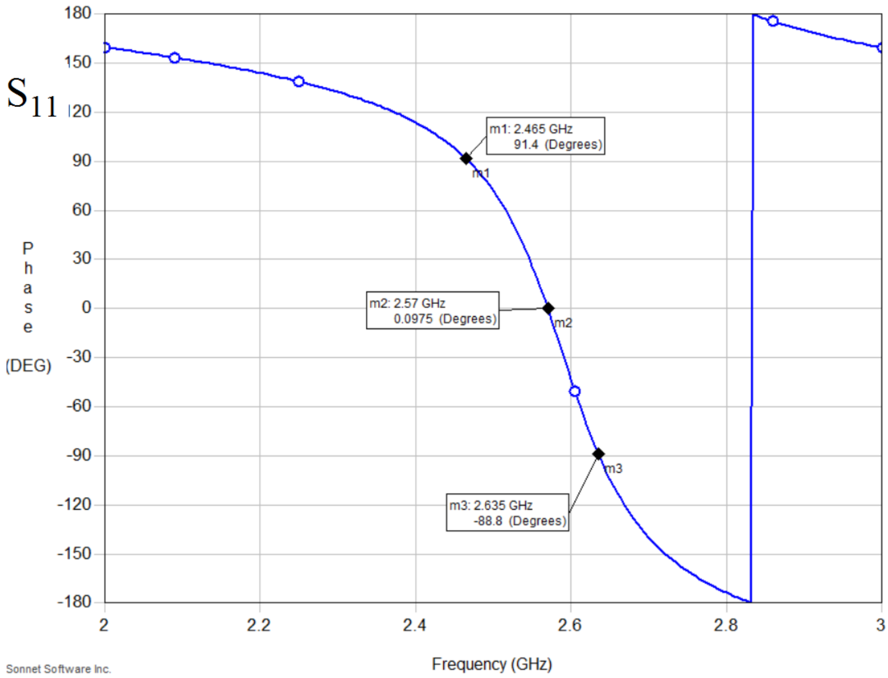

Fig. 8 The phase of the reflection factor for t=1.9 mm

Fig. 9 shows the external quality factor in dependency on the distance from the bottom side *t* for all three systems.

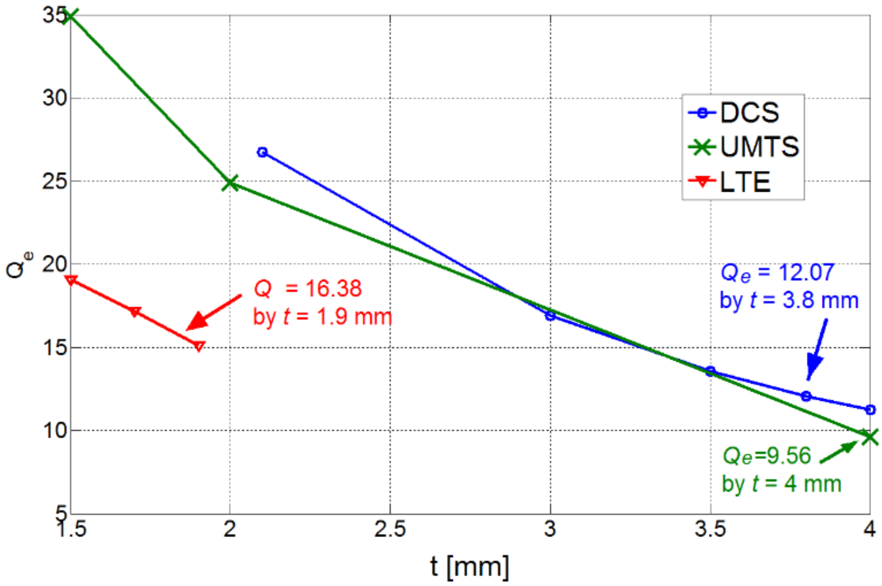

Fig. 9. External quality factor as function of distance *t*.

From the information in Fig. 9, we can extract the distance *t* by given values of the external quality factors above. The external quality factor of 12.07 for DCS can be gained by setting *t*=3.8 mm, equivalently for UMTS *t*= 4.0 mm and for LTE *t*=1.9 mm. In this way, we should get good matching condition for each application.

3. BANDPASS FILTERS FOR DCS, UMTS AND LTE – SIMULATION AND VERIFICATION

With the dimensions gained in section II, we can model three bandpass filters, as shown in Fig. 10. The feeding line from the ports to tapping position at the filter is a 50 Ω-line, the width of this line is calculated to *w*=0.63 mm, which is approximated by 0.6 mm.

The calculation of the filters is carried out by the commercial software Sonnet v.15. Fig. 11 shows the reflection and transmission factors for the filters.

The result of DCS filter has the 3dB-range from 1709.8 MHz to 1894.3 MHz (specs given is 1710.2 MHz to 1879.8 MHz). The insertion loss is better than 1.5 dB with some deterioration in the lower band to about 3.5 dB loss. The return loss is better than 10 dB (10% total power is reflected back), with some deterioration in the lower band.

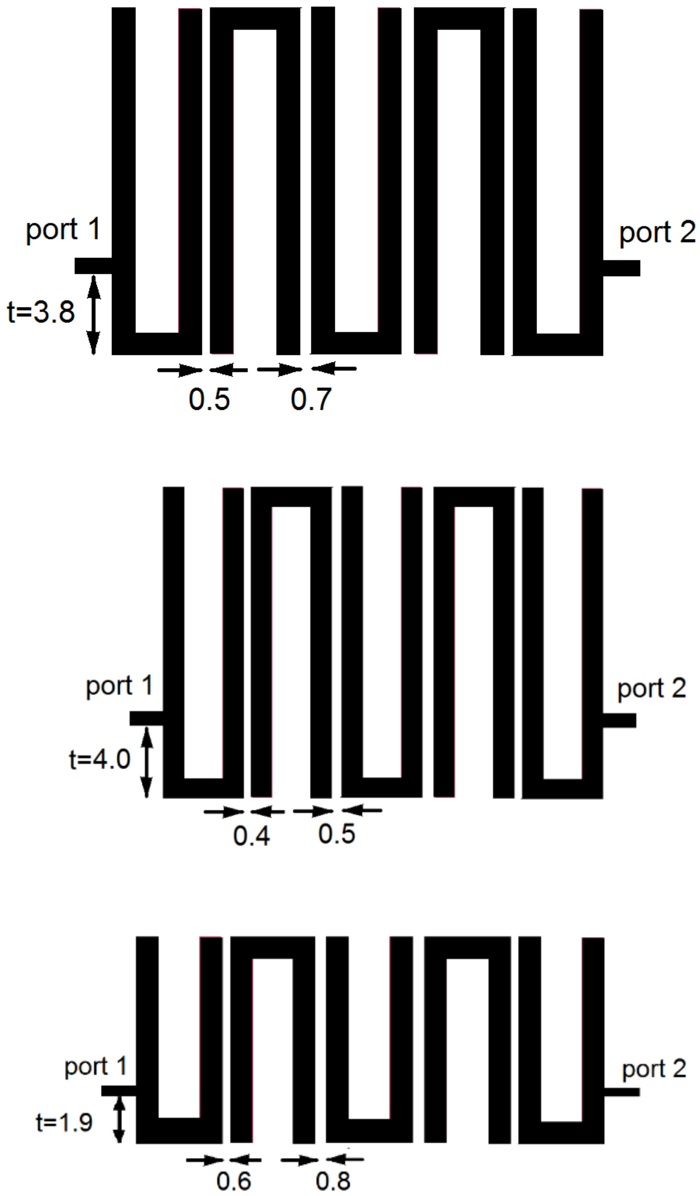

Fig. 10. Designed bandpass filters (top) DCS, (mid) UMTS (bottom) LTE, all dimensions in mm.

The result of UMTS filter has the 3dB-range from 1966 MHz to 2245.3 MHz (specs given is 1920 MHz to 2170 MHz). This frequency region is about 46 MHz shifted to higher region than planned in the specifications. It means, we dimensioned the filter little bit smaller than required to fulfill the specs.

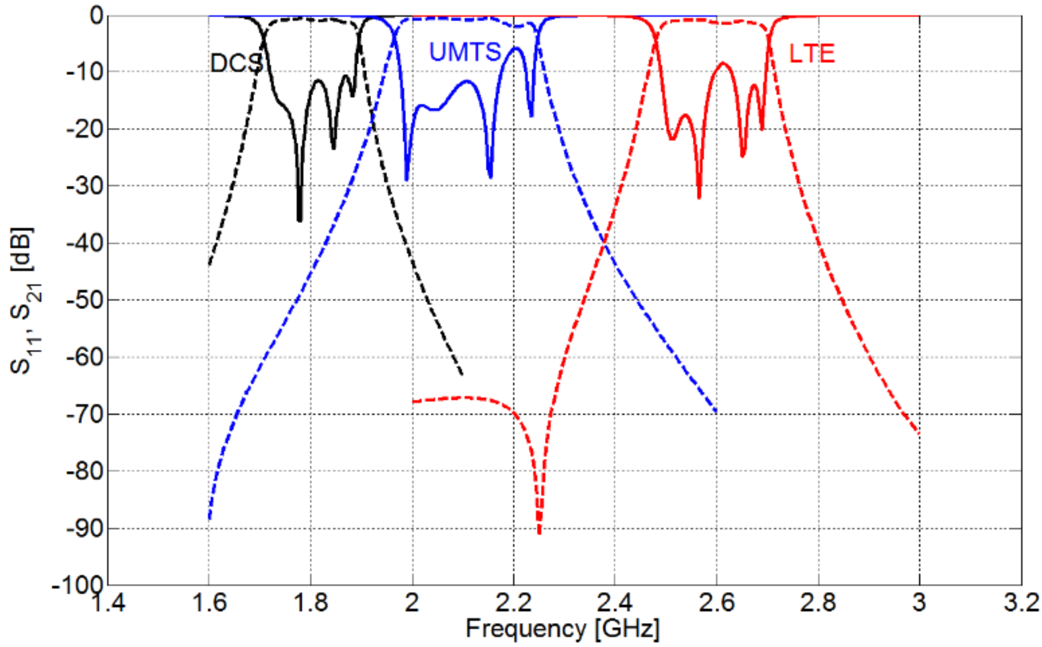

Fig. 11. Simulation results of reflection and transmission factors for DCS, UMTS and LTE.

The result of LTE filter has the 3dB-range from 2481.6 MHz to 2700.4 MHz (specs given is 2500 MHz to 2690 MHz). This frequency region has wider bandwidth. The consequence of such wider frequency interval can cause interferences and more noise.

Fig. 12 shows the prototype of the filters connected with SMA connectors as input and output ports.

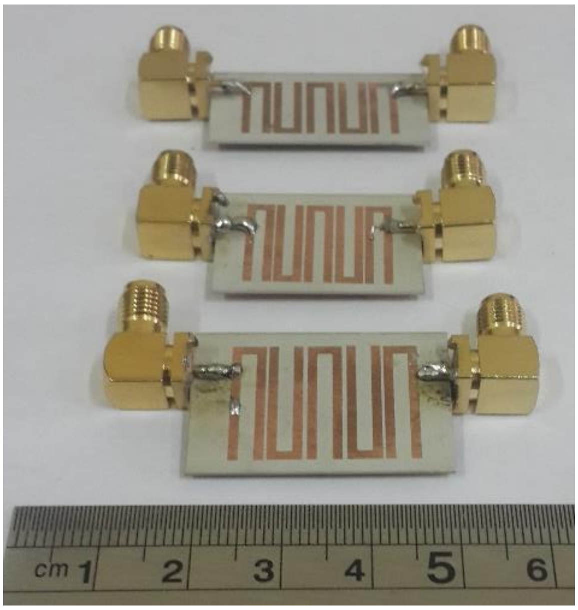

Fig. 12. Prototype of the designed bandpass filters (bottom) DCS, (mid) UMTS (top) LTE.

The prototypes are measured by a network analyzer ZVL13. The reflection factors of the filters are depicted in Fig. 13. In general, the measurement verified the design process. The measurement shows the prototypes have wider bandwidth than the simulation results. The reflection factors for all filters are also worse, it increases to -5dB, the reason is eventually due to the soldering of the SMA connectors to the strips.

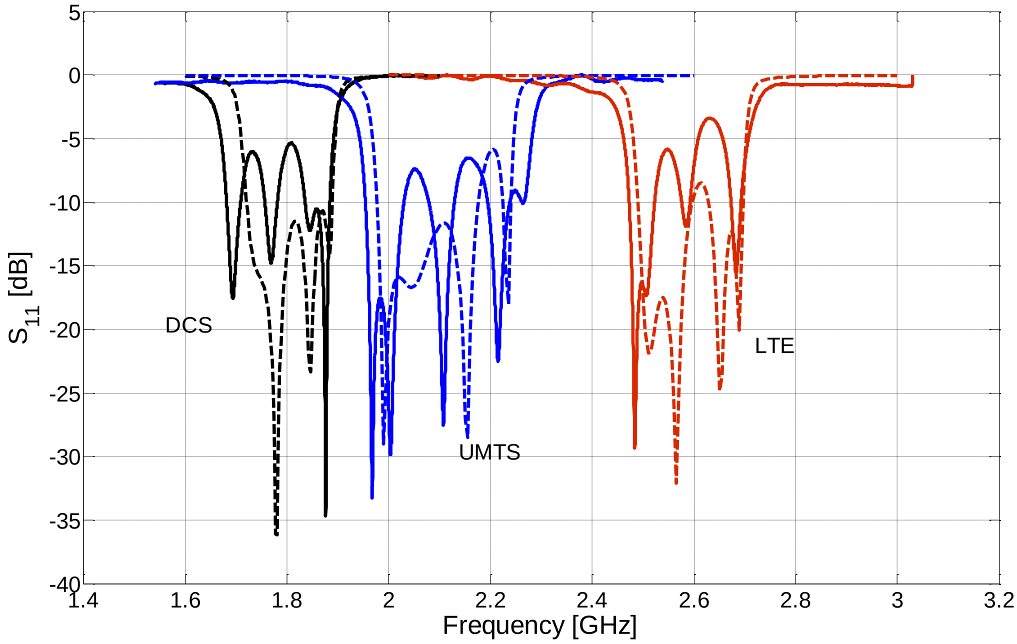

Fig. 13. Calculated (dashed) and measured (solid) reflection factor.

The transmission factors measured are compared with the simulation in Fig. 14. The measurement verified the calculation very well. We see rejection of more than 40 dB in each band. However in the passband, an insertion loss of about 3 dB higher than the simulation is observed. The reason could come from the effects of the connectors and its bad soldering to the filters. This must be taken into account in the planning of the power budget.

5. CONCLUSION

In this work, three bandpass filters based on hairpin line are designed for DCS, UMTS and LTE systems. The filters are implemented in microstrip technology. The designed filters conform in general with the specifications given in the standards. The comparison with the measurements in general verified also the whole design process. The reflection factors of the prototypes deteriorates significantly. The values increase to -5 dB, which is caused probably due to bad soldering of the connectors to the filters. The insertion loss of the filter prototypes are about -2 dB and -5 dB.

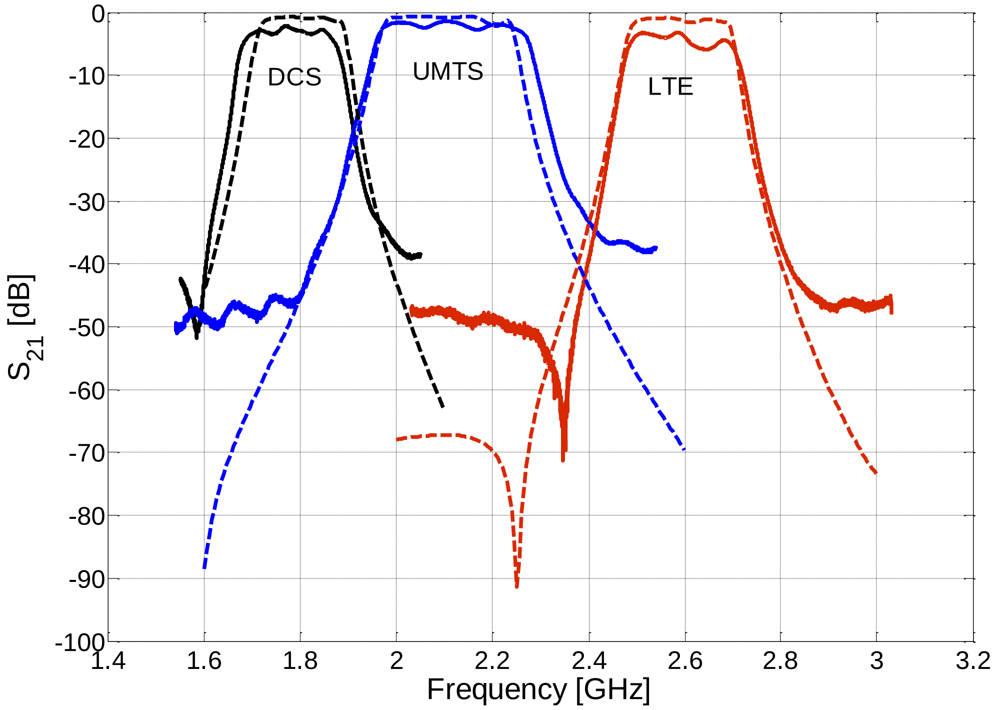

Fig. 14. Calculated (dashed) and measured (solid) transmission factor.

REFERENCES

[1] M.Alaydrus, D. Widiastuti and T. Yulianto, Designing Cross-Coupled Bandpass Filters with Transmission Zeros in Lossy Microstrip, IEEE ICITEE 2013– The 5th International Conference on Information Technology and Electrical Engineering, 7-8 October 2013, Jogjakarta.

[2] D. W. Astuti, Juwanto and M. Alaydrus, A Bandpass Filter Based on Square Open Loop Resonators at 2.45 GHz, ICICI BME 2013, November 2013, Bandung.

[3] Y.H.Lee, W.H. Kwon, B.H. Koo, C.S. Lee, A study on a RF filter of IMT-2000 terminal using coupled rectangular microstrip loop resonators, Asia-pacific Microwave Conference 1999, pp.295-298.

[4] H. Miki, Z. Ma, and Y. Kobayashi, A Novel bandpass filter with sharp attenuations and wide stopband developed through the combined use of composite resonators and stepped impedance resonators, Asia-pacific Microwave Conference 2006, pp. 1683-1686.

[5] O.A.R. Ibrahim, I.M. Selamat, M. Samingan, M. Aziz, A. Halim, 5.75 GHz microstrip bandpass filter for ISM band, Applied Electromagnetics, 2007 Asia-Pacific Conf. on, Dec. 2007, pp. 1-5.

[6] A. Naghar, O. Aghzout, F. Medina, M. Alaydrus, M. Essaidi, "Study and Design of a Compact Parallel Coupled Microstrip Band-Pass Filter for a 5 GHz Unlicensed Mobile WiMAX Networks", International Journal of Science and Technology, vol. 2, No. 6, June 2013.

[7] 3GPP TS 05.05 version 8.20.0 Release 1999 Pages 9 and 10.

[8] 3GPP Specifications for group: R4 - Frequencies info for UMTS (TS 25.101/102/104/105)

[9] 3GPP TS 36.101 E-UTRA: User Equipment (UE) radio transmission and reception[

[10] A.Al-ghoul, Design of UMTS/LTE Diplexer and DCS/UMTS/LTE Triplexer for Mobile Communication Systems, Master Thesis, Islamic University of Gaza, 2013.

[11] J.-S. Hong, Microstrip Filters for RF/Microwave Applications, 2nd ed., Wiley, 2011.

[12] Rogers corporations, www.rogerscorp.com (accessed 20 August 2015)

[13] M. Alaydrus, Transmission Lines in Telecommunication, Graha Ilmu Press, Jogjakarta, 2009