

스마트그리드 IED용 대역통과여파기 소형화를 위한 메타재질구조 설계법 연구

논문
60-12-20

Study on the Metamaterial Design Methodology to Reduce the Size of the Bandpass Filter for the Smart Grid IED

강 승 택* · 김 형 석†
(Sungtek Kahng · Hyeong-Seok Kim)

Abstract - In this paper, we propose the methodology to make the bandpass filters for the Smart Grid IED(Intelligent Electronic Device) smaller than the conventional bandpass filters. The size-reduction of the filters and the filter performances are indebted to devising small CRLH(composite right- and left-handed) resonators and coupling them as the metamaterial structures. The design methodology is validated by the equivalent circuit to be compared with the reliable full-wave EM simulation, and the proposed metamaterial filter outperforms the standard parallel-edge coupled filter with respect to the miniaturization and frequency response.

Key Words : Smart grid IED, Metamaterial, CRLH Bandpass filter

1. Introduction

As the volume of the industry is huge and heavy, the demand on electric power becomes rapidly growing and tremendous. Also, the household consumes electric power more and more with an increasing number of home appliances. The power consumption goes excessive and will cause the power-outage like the trouble North America underwent some years back. A while ago, there was a blackout all across the country in Korea and the entailing and frustrating accidents were reported. This has motivated people to make the electric power distribution grid smart by providing the functions of monitoring and reporting events and shooting troubles.

The Smart Grid has the same idea and objectives as the above, and been dealt with in the level of the functional block diagram for years. But the hardware and software for the Smart Grid have been defined since not long ago. The hardware needed in this field is the monitoring system for the nodes of the electric power web as well as the wired and wireless communication systems for the inter-node and node-to-controller. The software goes together with the hardware and micro computers as the DSP and modem techniques. One good example of the monitoring system is the PDM(partial discharge monitor)[1]. The data gathered from the

sensors in the PDM are processed in the digital board of the IED(intelligent electronic device) and changed to the baseband signals which will be transferred to the control center[2]. If the signal is transmitted from the IED or PDM at one node of the grid to another or the far-away control center, the RF system block is required for the wireless communication. The wireless communication system can be expressed as follows.

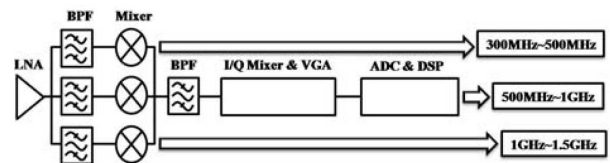


Fig. 1 RF system block for the monitoring device(e.g. IED) of a node in the Smart Grid

As shown in Fig. 1, the RF system is a type of repeater where the LNA at the end of the reception antenna is followed by the channel splitter that divides the wideband signal to three channels. The three channels are 300MHz~500MHz, 500MHz~1GHz, and 1GHz~1.5GHz which have their own bandpass filters and mixers. These passive and active components see the base-band block as their next stage. The baseband functions including the ADC and the DSP are available outside the scope of this research work. The bandpass filters and frequency converters are the items to be designed, but since the solutions to the mixers for the frequency bands above can be given not hard, filters will be designed, because the filters are the key component to

* 정 회 원 : 인천대학교 정보통신공학과 교수

† 교신저자, 시니어회원 : 중앙대 전자전기공학부 교수

E-mail : kimcaf2@cau.ac.kr

접수일자 : 2011년 10월 28일

최종완료 : 2011년 11월 25일

determine the overall size and characteristics of the system. Furthermore, though lumped element filters come to the designers' mind in the first place, distributed element filters are preferred in terms of controlling the spurious frequencies and removing the matching network for commercial lumped elements like chip inductors and chip capacitors. Besides, among the three bandpass filters, the one for channel 1 is chosen, since its frequency is the lowest and drives the designers to find the solution to the small size in the form of a distributed element structure.

The size-reduction of a filter has been tried in a variety of ways. Meandering and loading techniques are often adopted, but they have many limits in the size-reduction and questions on controllability that the requirements are met[3]. Mostly, as the conventional distributed type filters suffer from the constraint on size-reduction due to the practice that resonators are fixed as half-wavelength, other approaches were suggested: DGS(defected ground structure) and SIR(steped impedance resonator). In [4], the traditional resonators are mixed with the DGS which separates the successive elements on the top and bottom of the substrate. The overall size is not significantly reduced from the half-wavelength case. The SIR was used to shift the first harmonic away from the fundamental frequency, but the building blocks for the resonance are around half-wavelength[5].

For the last decade or more, metamaterials have intrigued RF component and system developers who seek

for the ways to make compact devices and improve the electrical and RF properties[6-11]. H. Okabe et al added the multiple cells of the left-handed transmission section that make the dispersion curve non-linear and increase the passband to a right-handed hybrid ring while keeping the original footprint[6]. S. Kahng et al came up with one cell CRLH resonators and coupling structures between the subwavelength resonators to the compact bandpass filters for the very wideband or multi-band as the UWB, the WLAN, and the UHF and ISM dual-band applications[7-11].

In this paper, the channel 1 bandpass filter for the PDM and IED in the framework of the Smart Grid implementation is designed using the metamaterial CRLH resonators and coupling elements to have the advantages in the miniaturized physical geometry and performances. Given the specifications, the transfer function is calculated as the first step. This mathematical expression is converted to the filter configuration and equivalent circuit that shows the metamaterial CRLH properties with the dispersion diagram in the second step. Based on the equivalent circuit, the physical filter structure is made and its frequency response is analyzed by the full-wave

EM simulator in the third step. The benefits of the proposed filter design is verified by the result that the CRLH filter is much smaller than the conventional one, and has the wider stopband.

2. CRLH bandpass filter design and verification

Prior to the design process, the specifications are given like the following

Table 1 Specifications on the bandpass filter for channel 1 of the PDM & IED

Band	300~500 MHz	Center frequency = 400MHz
Passband	Insertion loss < 2dB	Return loss \cong 15dB
Stopband	No first harmonic	Filter order \geq 3

As mentioned earlier, since the filter for channel 1 as the lowest band tends to be the longest and its design is challenging. While the size is concerned, its target frequency response from Table 1 results in the transfer function and scattering parameters.

$$S_{21} = \frac{1.638}{S^3 + 1.939S^2 + 2.629S + 1.638} \quad (1)$$

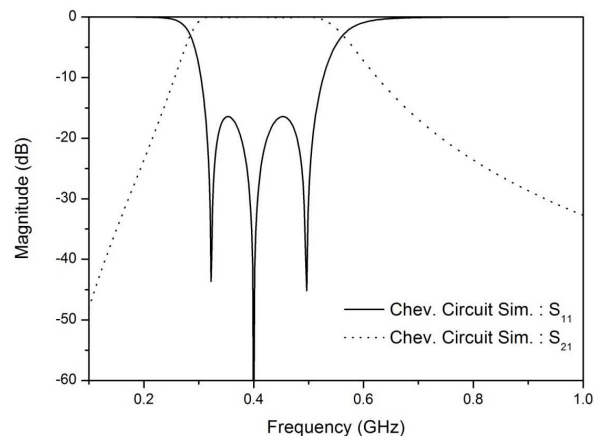


Fig. 2 Transfer function and its s-parameters

The transfer function has three poles in the passband ranging from 300MHz through 500MHz, and the insertion loss and return loss are 0dB and 17dB, respectively as the ideal case. Also, in this mathematical result, there is no harmonic, but when it is implemented as the distributed element, spurious frequencies will occur in the conventional technique.

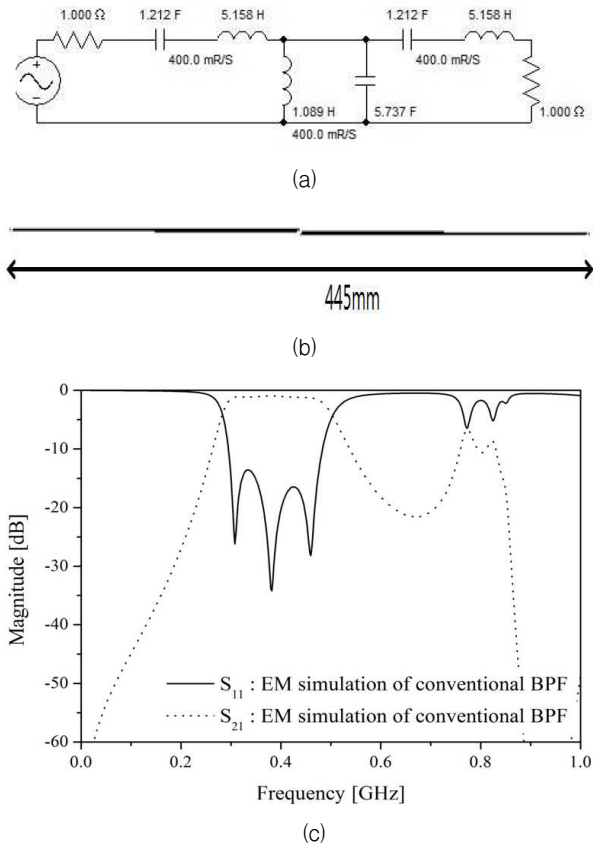


Fig. 3 Conventional equivalent circuit and standard parallel edge coupled filter (a) Conventional equivalent circuit with ideal lumped element (b) Standard parallel edge coupled filter (c) S_{11} and S_{21} of parallel edge coupled filter

The transfer function is converted to the conventional equivalent circuit with ideal lumped elements as Fig. 3(a) This circuit is not realistic. So the parallel edge coupled filter shown in Fig. 3(b) is adopted as the distributed element structure for the transfer function. Fig. 3(c) shows the target passband is achieved, but in the stopband the first harmonic is created at 800MHz which prevents this filter from the wide-stopband. To improve the stopband and decrease 445mm the length of the entire filter, the CRLH approach is presented from now on.

When the resonators are small, the overall size of the filter will be reduced. So the new equivalent circuit suggested in Fig. 4(a) in this paper consists of the three resonator tanks that are coupled through the inverters. Each tank resonator should have the CRLH configuration to bring the miniaturization due to the phase compensation between the LH and RH as in Fig. 4(b). Simultaneously, the inverter comprises the $L_{inverter}$ and $C_{inverter}$ as in Fig. 4(c). The circuit elements for the unit resonator tank are calculated to meet the specifications.

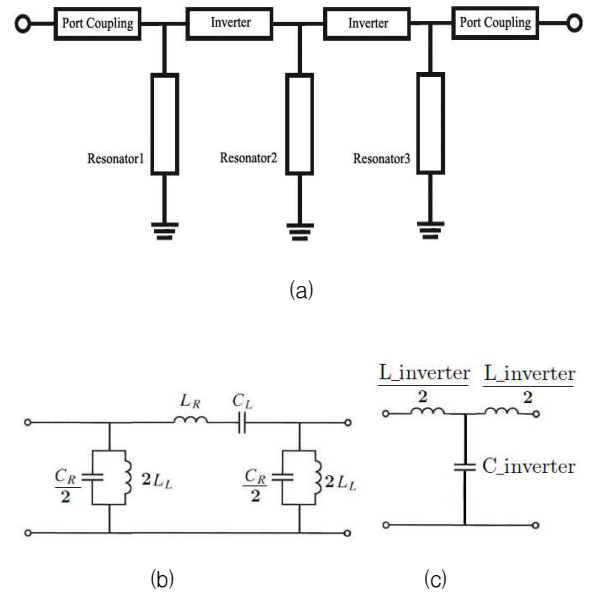
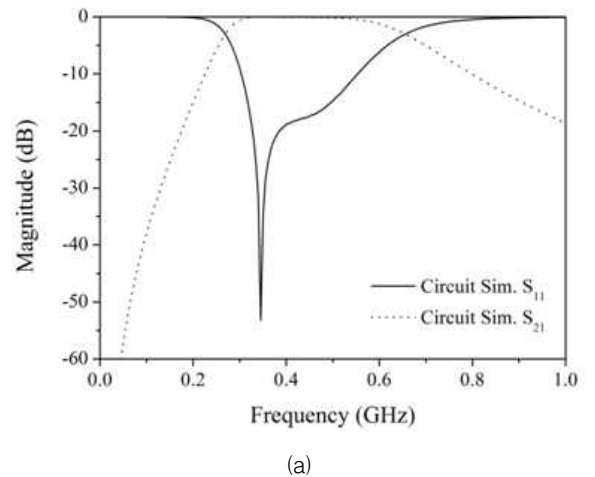


Fig. 4 Proposed equivalent circuit (a) Three resonator tanks coupled through the inverters (b) $-$ type CRLH configuration for each tank resonator (c) Inverter as the coupling element

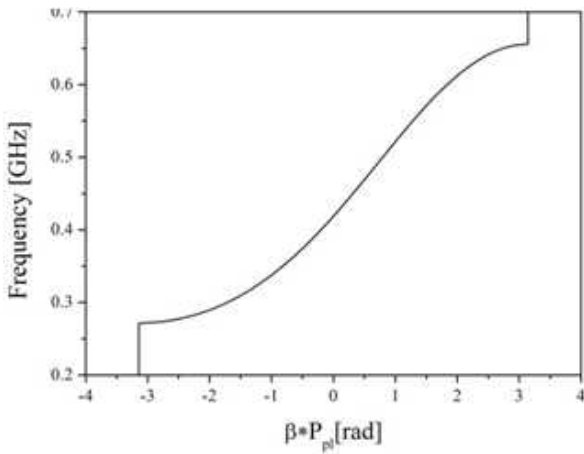
Table 2 Circuit elements for the unit CRLH resonator tank

Element	Value	Element	Value
L_L	13.8 nH	L_R	56.1 nH
C_L	2.8 pF	C_R	11.3 pF

In this step, the resonator tanks are the same because the coupling between the resonators is going to be considered later. Using the elements from Table 2, each and every CRLH resonator tank provides



(a)



(b)

Fig. 5 The characteristics of the unit CRLH resonator tank as the equivalent circuit (a) Scattering parameters (b) dispersion diagram

Fig. 5(a) presents the band, insertion loss, and return loss, and the stopband results of the unit resonator tank comply with the specifications. Fig. 5(b) is the dispersion diagram where (propagation constant) becomes negative(LH) or positive(RH) with reference to the zeroth order resonance at 400MHz, which proves the metamaterial CRLH properties. Due to having the non-linear dispersion characteristics with the zeroth order resonance, the harmonic at 800MHz has disappeared. However, we have mentioned the unit CRLH resonator tank, not a complete filter. By coupling the resonators with the inverters as Fig. 4(c), we can make a bandpass filter as follows.

Table 3 Circuit elements for the CRLH bandpass filter

Element	Value	Element	Value
L_L	8.8 nH	L_{L2}	6.4 nH
L_R	42.9 nH	L_{R2}	48.8 nH
C_L	3.5 pF	C_{L2}	3.1 pF
C_R	15.0 pF	C_{R2}	9.6 pF
$C_{inverter}$	8.2 pF	$L_{inverter}$	0.7 nH

Though we have moved from the resonator to a filter, the specifications should still be met. Entering the values from Table 3 into Fig. 4, the circuit simulated frequency response is obtained as follows.

As is clearly seen in Fig. 6, the band, the insertion loss and the stopband are compliant with the specifications. Now, the circuit is physically implemented following the conversion techniques in [7-11].

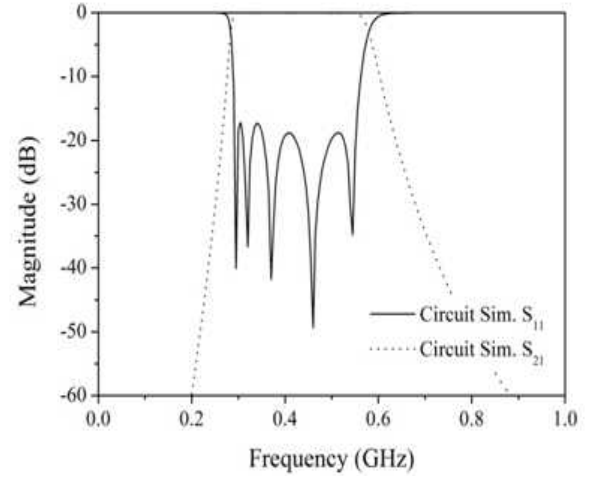
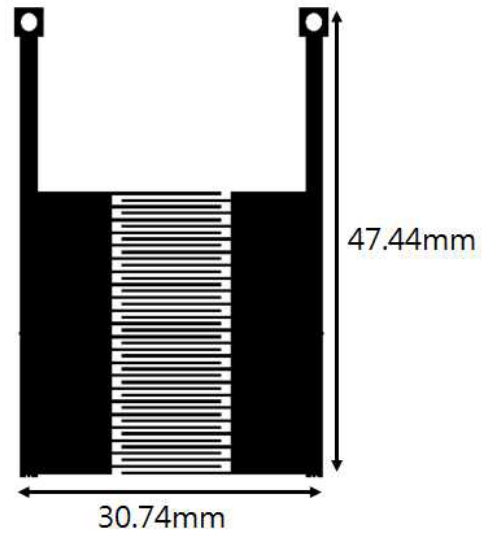
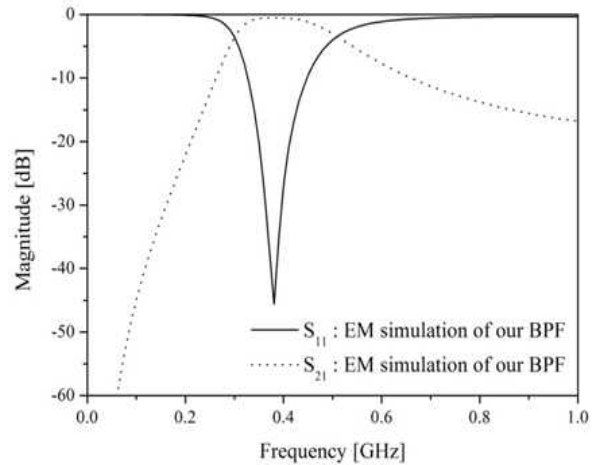


Fig. 6 Circuit simulated frequency response of the equivalent circuit of the CRLH filter



(a)



(b)

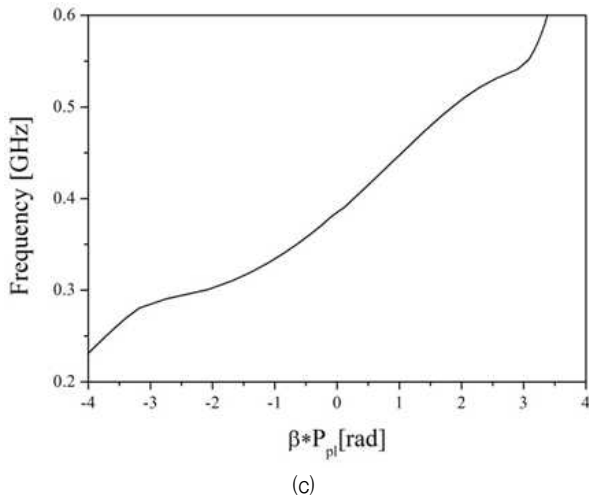


Fig. 7 The characteristics of the unit CRLH resonator tank as the implemented geometry (a) physical structure (b) Scattering parameters (c) dispersion diagram

Fig. 7(a) is the physically implemented version of the equivalent unit CRLH resonator tank in Fig. 5(a). It is the microstrip with FR4 as the lossy substrate ($\epsilon_r=4.4$ and $\tan\delta=0.02$). Slightly different from the equivalent circuit, the bandwidth in Fig. 7(b) becomes narrower, because of the complicated interactions across all the parts of the real structure in Fig. 7(a), and the diminished quality-factor by the loss of the dielectric substrate. Nevertheless, we are just standing in the level of the resonator, not the entire filter. What is coming later is controlling the coupling between the CRLH resonator tanks and meeting the design requirements. Fig. 7(b) is the dispersion diagram calculated from the scattering parameters of the implemented resonator where β becomes negative(LH) or positive(RH) with respect to the zeroth order resonance at 400MHz, which is the same phenomenon as Fig. 5(b) as the metamaterial CRLH properties. On account of the non-linear dispersion characteristics over the LH through the zeroth order resonance to the RH region, the harmonic at 800MHz typical to the linear dispersion case has been shifted away in the frequency region of observation. Based upon this kind of resonator, the following physical structure of the filter is suggested by combining the CRLH resonators with the realized coupling elements to finalize the design process.

In the complete geometrical form of the CRLH bandpass filter in Fig. 8(a), the resonator tanks are combined with narrow lines as the coupling elements. The total length of the proposed filter reads 287.57mm, which is much smaller than that of the parallel edge coupled filter mentioned earlier. Also it is noteworthy that as the resonator of Fig. 3(b) as the conventional filter is 222.5mm long and the length of the proposed CRLH

resonator tank is 30.74mm, we experience the size-reduction of factor of 7.4. The bandwidth of Fig. 7(a) has been retrieved in Fig. 8(b) owing to controlling the coupling between the resonators. Along with this, the insertion loss and return loss over the passband are 1.7dB and 10dB, respectively, acceptable to the RF system development and supposed to be tuned further(more iterations of trimming and using lower loss substrates). And it is observed that this filter has no harmonic up to 1GHz without an extra circuit such as a lowpass filter.

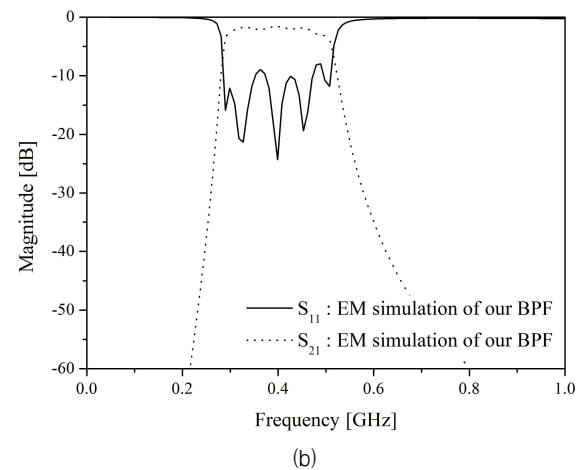
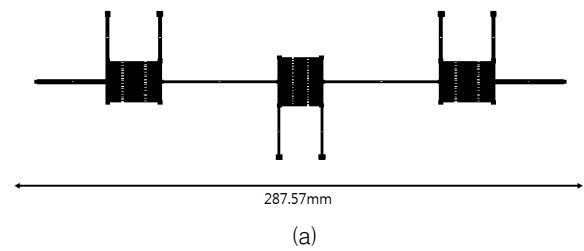


Fig. 8 The proposed CRLH filter for the Smart Grid IED and its characteristics (a) physical structure (b) Scattering parameters

3. Conclusion

The design methodology is studied to make a miniaturized bandpass filter for channel 1 in the RF block of the Smart Grid IED. The resonators and filter can be implemented compact using the CRLH configuration and structure. The coupling elements are used to control the interaction between the resonators to meet the passband and stopband specifications. The equivalent circuit related to the transfer function, circuit simulation and metamaterial properties are validated, and the acceptable frequency response and the size reduction effect are presented in comparison to the conventional filter.

감사의 글

본 연구는 지식경제부의 지원에 의하여 기초전력연구원(2009T100100596) 주관으로 수행된 과제임.

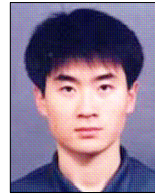
참 고 문 헌

- [1] 최태식, 정재룡, 김민수, 김정배, 송원표, 이학성, "GIS 부분방전 측정 휴대용 On-Line iPDM 시스템 개발," 대한 전기학회 고전압 및 방전응용기술 연구회, 2006
- [2] Gun-ho Jang, Sungtek Kahng, Hyun Baek, Hyeongseok Kim, "Analysis of Interference on the Signal over the Multiple TX-Lines of a Trace Layer in an IED," 2009 KIEE the 40th Summer Conference Proceedings, 2009.7
- [3] Haiwen Liu, Reinhard H. Knoechel, and Klaus F. Schuenemann, "Miniaturized Bandstop Filter Using Meander Spurline and Capacitively Loaded Stubs," ETRI Journal, Volume 29, Number 5, pp.614-618, October 2007
- [4] G.-L. Wu, W. Mu, X.-W. Dai, and Y.-C. Jiao, "Design of novel dual-band bandpass filter with microstrip meander-loop resonator and CSRR DGS," Progress In Electromagnetics Research, Vol. 78, 17-24, 2008.
- [5] Xiao, J.-K., S.-W. Ma, S. Zhang, and Y. Li, "Novel compact split ring stepped impedance resonator (SIR) bandpass filters with transmission zeros," Journal of Electromagnetic Waves and Applications, Vol. 21, No. 3, 329 - 9339, 2007.
- [6] H. Okabe, C. Caloz, and T. Itoh, "A compact enhanced-bandwidth hybrid ring using an artificial lumped-element left-handed transmission-line section," IEEE Transactions on Microwave Theory and Tech., vol. 52, no. 3, pp. 798-804, March 2004.
- [7] S. Kahng, and J. Ju, "Design of the UWB bandpass filter based on the 1 cell of microstrip CRLH-TL," Proc. International Conference on Microwave and Millimeter Wave Technology (IEEE-ICMMT 2008), Vol. 1, pp. 69-72, 2008.
- [8] S. Kahng, and J. Ju, "Realized metamaterial crlh bandpass filter for UHF-band WLAN with harmonics suppressed," IEEE MTT-S International Microwave Workshop Series on: Art of Miniaturizing RF and Microwave Passive Components, 2008.
- [9] G. Jang, and S. Kahng, "Design of a Dual-Band Metamaterial Bandpass Filter using Zeorth Order Resonance," Progress In Electromagnetics Research C, Vol. 12, pp. 149-162, 2010
- [10] J. Ju and S. Kahng, "A compact UWB bandpass filter using a center-tapped composite right/left-handed transmission-line zeroth-order resonator,"

Microwave and Optical Technology Letters, Vol. 53, Issue 9, pp. 1974-1976, 2011

- [11] Sungtek Kahng, "Ultrawideband Bandpass Filter Using Composite Right- and Left-Handedness Line Metamaterial Unit-Cell," Chapter 20 of 'Advanced Microwave and Millimeter Wave Technologies Semiconductor Devices Circuits and Systems', pp.395-402, InTech, March 2010

저 자 소 개



강 승택 (姜勝澤)

2000년 한양대학교 전자통신 공학박사
2000년 한양대학교 산업과학연구소 연구원
2004년 한국전자통신연구원 통신위성개발센터 선임연구원
2004~현재 인천대학교 정보통신공학과 교수
2007~현재 송도 국방벤처 자문교수
[주 관심분야] 전자파 수치 해석 및 응용, EMI/EMC 대책, 초고주파 부품 및 안테나 설계, 메타재질구조 이론 및 응용



김형석 (金炯碩)

1985년 서울대학교 전기공학 공학사
1987년 서울대학교 전기공학 공학석사
1990년 서울대학교 전기공학 공학박사
1990~2002년 순천향대학교 정보기술공학부 교수
1997~1998년 R.P.I ECSE, USA 방문교수
2002년~현재 중앙대학교 전자전기공학부 교수
[주 관심분야] 전자장수치해석, 전자기기 및 소자 해석 및 설계, 전력설비 모니터링 시스템, SoC 응용회로, EMI/EMC, RFID 응용 기술