Microstrip Cross-coupled Interdigital SIR Based Bandpass Filter

Ram Krishna MAHARJAN, Bhanu SHRESTHA, Nam-Young KIM

Dept. of Electronic Engineering, Kwangwoon University, Nowon-gu, Seoul 139-701, Korea

rkmahajn@gmail.com, bnu@kw.ac.kr, nykim@kw.ac.kr

Abstract. *A simple and compact 4.9 GHz bandpass filter for C-band applications is proposed. This paper presents a novel microstrip cross-coupled interdigital half-wavelength stepped impedance resonator (SIR) based bandpass filter (BPF).The designed structure is similar to that of a combination of two parallel interdigital capacitors. The scattering parameters of the structure are measured using vector network analyzer (VNA). The self-generated capacitive and inductive reactances within the interdigital resonators exhibited in a resonance frequency of 4.9 GHz. The resonant frequency and bandwidth of the capacitive cross-coupled resonator is directly optimized from the physical arrangement of the resonators. The measured insertion loss (S_{21}) and return loss (S_{11}) were 0.3 dB and 28 dB, respectively, at resonance frequency which were almost close to the simulation results.*

Keywords

Bandpass filter, interdigital resonator, stepped impedance resonator (SIR), half wavelength SIR resonator.

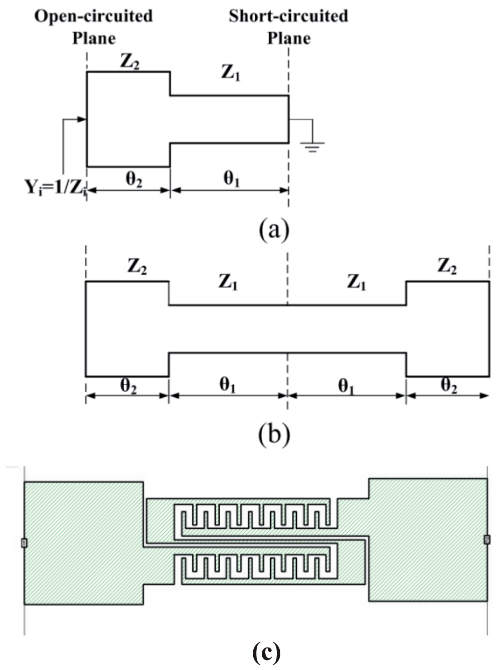

Fig. 1. The basic structures of SIR resonators: (a) Quarter-wavelength type. (b) Half-wavelength type. (c) Proposed λ/2 structure of CISIR.

1. Introduction

Bandpass filters are essential devices, commonly found in both receivers and transmitters in the various fields of communication systems, such as mobile phones, terrestrial networks, satellite communications, and many other contemporary applications [1]. However, the technical limitations of the lump elements RLC, such as precise value problem, mounting problem, costly less tolerance components, discrete components occupy larger space, discrete inductor itself bulky, difficult to manage in RF circuitry, lump components consume larger power, and susceptibility to parasitic effects in the gigahertz range. In fact, the discrete components consume much current because a resistor, R dissipates power as an ohmic loss (I^2R) and also converts into heat energy which is also proportional to the size of component itself. Similarly the bulky discrete inductors naturally leak unnecessary more magnetic flux while converting electric current into magnetic field and larger size capacitors also lose some more electric field as the electric current passes through them. The quality of bandpass filers is extremely important. Thus, small size and high performance filters are needed to reduce the cost and improve the system performance. They can be designed in many different ways. Planar filters provide good miniaturization ability. The planar filters have been fabricated using printed circuit technology and are suitable for commercial applications due to their small size and lower fabrication cost [2]-[4]. A conventional haft-wavelength open line microstrip resonator is too large to be used in the modern communication system such as 900 MHz, 1800 MHz for personal communication systems (PCS). The compact high performance microwave bandpass filters are highly desirable in the modern wireless communications systems. The designed hairpin filters [5]-[8] were folded from the open line λ/2 wavelength microstrip resonator to become U-shaped resonators make progress in circuit size reduction from the parallel-coupled line structure. Since 1989, practically the miniaturized hairpin resonator was developed by several researchers, [9]-[12]. Since microstrip resonators are the basic components of a planar filter design, it is necessary to select proper resonator types used in a filter design.

In this paper, a design of cross-coupled interdigital stepped impedance resonator based bandpass filter is proposed. The interdigital cross-coupled lines at the center of this λ/2 wavelength structure are applied as capacitors in order to reduce the resonator size. It is also possible to use in microwave oscillator to get a low phase noise characteristics [13]. As well as, the interdigital cross-coupling is used to providing strong electromagnetic coupling for getting more capacitive effect to achieve required bandpass response and to get desired resonance frequency.

2. Proposed BPF Design

The stepped impedance resonator (SIR) and its relevant design parameters are illustrated in Fig. 1. Fig. 1(a) and (b) show the basic structures of the quarter-wavelength ($\lambda/4$) and half-wavelength ($\lambda/2$) type SIR resonators, respectively. Each figure consists of the two different transmission line impedances of Z_1 and Z_2 with corresponding electrical lengths of θ_1 and θ_2, respectively. The impedance ratio, R_Z is the ratio of the two transmission line impedances Z_1 and Z_2. The R_Z is the most important parameter in characterizing properties and analysis of SIR structure. Basically, the fundamental resonance and the spurious resonances can be tuned by choosing a ratio of impedance, R_Z and the electrical length for determining the fundamental frequency at f_0. It is also used for finding resonator length and equivalent circuit analysis. The relation of the R_Z can be defined by the following equation:

$$R_Z = \tan\theta_1 \tan\theta_2 = Z_2 / Z_1 \tag{1}$$

where θ_1 and θ_2 are electrical lengths; and Z_1 and Z_2 are corresponding transmission line impedances belonging to different steps of the SIR structure. In general, θ_1 is often chosen to be equal to θ_2, similarly Z_1 is also chosen to be equal to Z_2, and then R_Z becomes 1. In this condition, the resonant frequency has been normalized with respect to the fundamental frequency of a short/open transmission line stub. If R_Z is larger than 1, the total length is longer than its normalized value, and if R_Z is smaller than 1, the total length is shorter than its normalized value. So, if the value of R_Z is determined, which means that the impedance elements, Z_1 and Z_2 are correspondingly determined as a ratio, there are two undetermined length parameters, θ_1 and θ_2. Then, either one of θ_1 or θ_2, is determined, the other θ_2 or θ_1, can be obtained by (1) [14]. The SIR has non-uniformly spaced resonant frequencies. The condition for determining the resonant frequency of input impedance toward pad-end in the image ground can be given by the following formula where the input impedance, Z_{in} is defined using R_Z as [14], [15]:

$$Z_{in} = -jZ_1 \frac{R_Z - \tan\theta_1 \tan\theta_2}{\tan\theta_2 + R_Z \tan\theta_1} = 0\,. \tag{2}$$

The impedance ratio in the quarter-wavelength SIR must be the half of half-wavelength SIR structure. Therefore, miniaturized resonator can be possible using λ/2, λ/4 wavelength SIR structures. In these types of SIR resonators, the resonator length and corresponding spurious resonance frequencies can be adjusted by changing the impedance ratio R_Z. If resonator electrical length $\theta_1 = \theta_2 = \theta_0$ in the SIR structure, the impedance ratio will be 1, therefore the resonant frequency can be normalized with respect to the fundamental frequency. Hence, these problems affect the electrical length of the resonator and the position of resonator associated with open-circuited stubs or shunt stubs of the bandpass filter structure [15].

3. Design Analysis and Simulation

The schematic of the center portion of the filter with its dimensions is illustrated in Fig. 2. The proposed design approach enables one to use Sonnet EM simulator to complete the filter design and to determine the physical dimensions of the filters. The resonant frequency and bandwidth can easily be varied by a slight change in the spacing between the interdigital arms, i.e. the width, length, and the gaps of separate parts of the structure. The structure applied in this paper is similar to that of combination of interdigital capacitors. The proposed CISIR filter is made using the half-wavelength SIR structure of 25 mm in length and 6.6 mm in width. The CISIR bandpass filter characteristics are generated by the split half-wavelength (λ/2) stepped impedance resonator structure using the inter-capacitive-coupling mechanism. The CISIR bandpass filter is more compact and has a sharp passband with a low insertion loss.

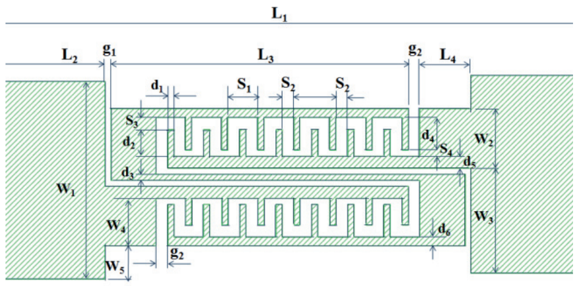

Fig. 2. Schematic of the proposed CISIR bandpass filter.

The equivalent circuit model of the CISIR design structure is adapted as a parallel circuit as shown in Fig. 3. Here, a sum of interdigital capacitances, the inter-electrode capacitances (stray capacitances) and the parasitic capacitances are modeled by overall equivalent parallel capacitances or just named interdigital capacitances, C_1 and C_2. They are considered as a parallel connected circuit including gap capacitances, C_{g1} and C_{g2}. The small value equivalent gap capacitances are considered due to the effects of small gaps, g_1 and g_2 in between the port 1 and port 2. Among many types of capacitances in the CISIR structure, the major role in the parallel capacitor is mainly depend on interdigital capacitive effects, therefore, the equivalent circuit model (Fig. 3) is assumed for interdigital capacitances. Other different kinds of capacitances and minor branch resistance-inductance values are not considered for simplifying the equivalent model. In simple analysis, the interdigital capacitor can be expressed as a series combination of resistor R, inductor L, and capacitor C (RLC model).

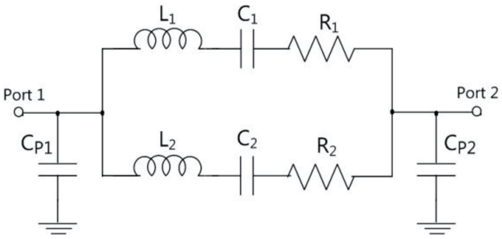

Fig. 3. Equivalent circuit of the CISIR bandpass filter.

From the physical structure of CISIR design layout, the interdigital capacitance value comparatively dominates the existing values of L and R, so that the structure is intentionally called as cross-coupled interdigital stepped-impedance resonator (CISIR) type. An equivalent inductive effect in the first interdigital capacitance (C_1) is modeled as L_1 and small value of equivalent resistance in series with those components is represented by R_1. Similarly, equivalent circuit components L_2 and R_2 belong to the second parallel branch of interdigital capacitance (C_2). We also assume an effect of the port pad (metal surface) through dielectric material-to-substrate metal (ground) capacitances which are considered as pad capacitances, C_{P1} and C_{P2} for the port 1 and port 2, respectively. The major circuit part of the planar CISIR equivalent circuit is between those pad capacitances. The self-resonant frequency is generated when two parallel interdigital resonators are electro-magnetically coupled each other in proper way. Hence, Fig. 3 demonstrates the parallel connection of two interdigital capacitors with symmetrical port 1 and port 2. The CISIR filter is designed by splitting the basic SIR structure. By splitting the SIR structure using the cross-coupled interdigital techniques, the overall CISIR length (L_1) becomes 25 mm. That means it saved 5 mm compared with standard half-wavelength SIR structure. It is the main concept applied to the proposed BPF design to get a desired resonance frequency and the bandwidth using splitting SIR structure.

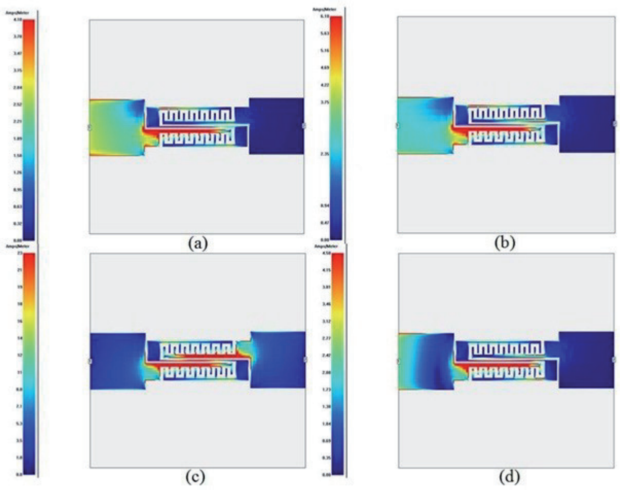

Fig. 4. The current distributions in the CISIR bandpass filter at (a) 3.5 GHz, (b) 4.0 GHz, (c) 5.0 GHz, (d) 6.0 GHz.

The current distributions of the proposed resonator at the different operating frequencies are illustrated in Fig. 4. The current distributions at randomly (a) 3.5 GHz, (b) 4.0 GHz, (c) 5.0 GHz and (d) 6.0 GHz were investigated using the Sonnet EM simulator. It also shows the current density conditions of the designed resonator at the significant states around the resonance conditions. Fig. 4(c) shows the essential state of equal and well current distribution at the 5.0 GHz resonant frequency compared to the other adjacent frequencies. The current distributions in the various operating frequencies were presented by the help of EM simulation while taking place in the design steps. At series resonance, the current distribution should be equal at resonance state, because the reactive components cancel each other and leave only the resistance, resulting in the maximum current flowing in that condition rather than those found in the other frequency bands. Fig. 5 shows the simulated S-parameter responses of insertion loss (S_{21}) of 0.25 dB and return loss (S_{11}) of 38 dB. It also shows the simulated resonance frequency of 5.0 GHz and 3dB passband bandwidth of 400 MHz. The CISIR bandpass filter design; analysis and simulation were accomplished with the help of commercially available computer aided design SONNET electromagnetic tool.

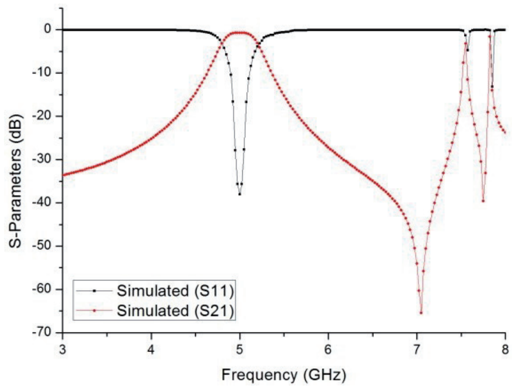

Fig. 5. Simulated S-Parameter responses of the CISIR.

4. Fabrication and Measurements

The proposed CISIR bandpass filter was fabricated on a Teflon substrate with the dielectric constant, ε_r of 2.52 and a thickness of 0.54 mm. The photograph of the fabricated CISIR bandpass filter is shown in Fig. 6. The proposed microstrip bandpass filter was fabricated with photolithographic and wet etching techniques. The overall physical size of the filter is of (6.6×25) mm^2. The designed CISIR bandpass filter has the following dimensions: $L_1 = 25$ mm, $L_2 = 6.4$ mm, $L_3 = 9.9$ mm, $L_4 = 1.7$ mm, $W_1 = 6.6$ mm, $W_2 = 2.0$ mm, $W_3 = 3.5$ mm, $W_4 = 1.6$ mm, $W_5 = 1.1$ mm, $S_1 = 1.0$ mm, $S_2 = 0.4$ mm, $S_3 = 0.4$ mm, $S_4 = 0.2$ mm, $d_1 = 0.2$ mm, $d_2 = 0.9$ mm, $d_3 = 0.2$ mm, $d_4 = 1.1$ mm, $d_5 = 0.4$ mm, $g_1 = 0.2$ mm, and $g_2 = 0.4$ mm. The CISIR is resonated at a 4.9 GHz center frequency with around 400 MHz effective bandwidth. The usable bandwidth of the CISIR bandpass filter is measured in 3 dB passband range. Furthermore, the coupling gaps g_1 and g_2

are narrow and thus remarkably more sensitive to fabrication unavoidable deviations than the other parameters [16]. The observed differences between the simulations and measurements can be attributed to the fabrication tolerances. The conductor loss, coupling loss, the dielectric loss and the non-ideal microstrip coaxial line transitions are thought to contribute to the higher insertion loss seen in the physical measurements compared to the simulation.

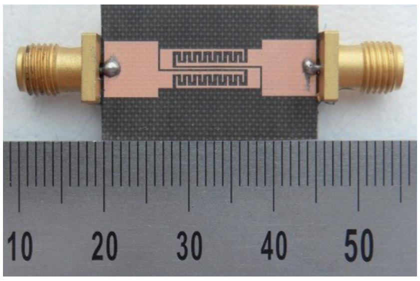

Fig. 6. Photograph of the fabricated CISIR bandpass filter.

The fabricated CISIR filter was measured using Agilent 8510C vector network analyzer (VNA). The measured insertion loss (S_{21}) and return loss (S_{11}) were 0.3 dB and 28 dB at the center frequency of 4.9 GHz. At the 4.9 GHz center frequency, this design was shown to have 3 dB passband; 400 MHz effective bandwidth was measured. Fig. 7 shows the S-parameter response comparison to both simulated and measured results. The graphical representation in Fig. 7 shows that the measured resonant frequency, f_0 of the CISIR filter was slightly drifted 100 MHz ahead from the simulated f_0 of 5.0 GHz. The cause of resonance around 7.8 GHz is the result of spurious resonances. In fact, the fundamental resonance and the spurious resonances can be determined by choosing the proper impedance ratio. In some cases, it may be slightly affected by the harmonic products and the effect of parasitic capacitances. The single mode simulated passband response was also changed to dual-mode response while measured in the experiment.

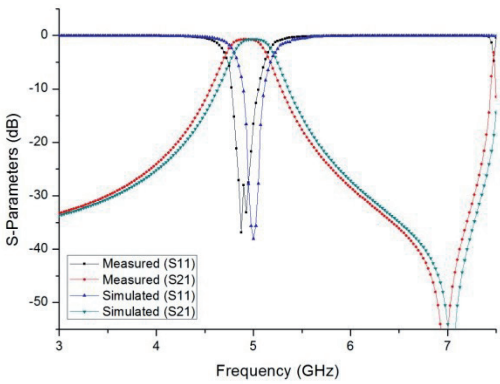

Fig. 7. Simulated and measured S-Parameter responses of the CISIR.

The simulated resonance frequency was set in single mode characteristic as depicted in Fig. 5, while the measured S-parameter responses were little bit shifted ahead about 0.1 GHz with dual-mode characteristic as shown in Fig. 7. The non-uniform dual-mode was recorded while measurement taken, its main causes can be due to minor misalignment of the RF coaxial connectors' orientation in the ports, soldering joints, and some electrostatic as well as parasitic capacitances effects during the measurement.

5. Conclusion

The proposed novel CISIR bandpass filter was fabricated on a Teflon substrate with the dielectric constant, ε_r of 2.52 and a thickness of 0.54 mm and characterized. It is designed that based on in the form of cross-coupled two interdigital resonators. The measured results of the BPF well agreed with simulation results since the return loss in the both simulation and measurement results shown below the 28 dB at the center operating frequency of 4.9 GHz. This is due to use of cross-coupled by splitting the basic SIR structure that results more coupling effect; the CISIR structure can be reduced more in size using monolithic microwave integrated circuit (MMIC) technology. The CISIR can be extensively used in low-power to medium-power C-band RF transceiver systems.

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About Authors …

Ram Krishna MAHARJAN received the B. S. and M. S. degrees in Radio Broadcasting/Communications and Television Engineering in 1993 and 1995 with Honors' respectively, from Tashkent Electro-technical Institute of Communications, Tashkent University of Information Technology, Uzbekistan, CIS, (former USSR). He won the Bright Student Honor Scholarship provided by the Government of the Former USSR and Uzbekistan together. He has been working as an Assistant Professor in Pulchowk Campus, Institute of Engineering of Tribhuvan University, Nepal from 29th Oct, 1995 to 14th Mar, 2012. Now, he is recently promoted as an Associate Professor since 15th Mar, 2012. He is currently pursuing Ph. D. Degree in the Department of Electronics Engineering, Kwangwoon University in Seoul, on the full Scholarship "Bright Korea 21st Century (BK21)" provided by the Government of the Republic of Korea since 1st Oct, 2008. His current research interests are in microstrip device design in RF/microwave & satellite communications, RFIC/MMIC circuits & system design and in the integrated passive device (IPD) design as well.

Bhanu SHRESTHA is born in Nepal and received the B. S., M. S., and Ph. D. degrees in Electronic Engineering from Kwangwoon University, Seoul, Korea in 1998, 2004 and 2008 respectively. He was an Adjunct Professor in the RFIC Center in the Department of Electronic Engineering, Kwangwoon University from March 2008 to Feb. 2011. He is currently working as an Assistant Professor at the same University. He was awarded the 'Bellwave Excellent Paper Award' by the Korea Institute of Electromagnetic Engineering and Science (KIEES) in 2005. He was also awarded a presidential award (Nepal Vidhya Bhusan 'Ka') conferred by the President of Nepal for his academic achievement in 2009. He is also a co-author of a book, 'Practical Design of MMIC VCOs'. His main research fields are RFIC/MMIC/HMIC circuit and system design. Currently, he is involving in designing and fabricating passive circuits in both hybrid and in Integrated Passive Device (IPD) Technology which are emerging technology.

Nam-Young KIM received two Masters and two Ph.D. degrees from the State University of New York at Buffalo and Midwest University: the M.S. and the Ph.D. in Electronic Engineering. He also received M. Div and D.C.E. degrees in Theology from Midwest University in 2004 and 2006, respectively. He was a research scientist of for CEEM at SUNY at Buffalo in 1994. After completing a research scientist of CEEM at SUNY at Buffalo, Prof. Kim joined the Department of Electronic Engineering of Kwangwoon University as an Assistant Professor in 1994. His main research focus is in RFIC device and system, which use wireless application techniques to develop high speed structures in GaAs, Si, and other materials. The founder in RFIC Education and Research Center, Prof. Kim also serves as a director for the Fusion Technology Center. His research center of RFIC was honored and sponsored as a ITRC (Information Technology Research Center) by the Ministry of Communication and Information (MIC) of Korea, where he has been acting Director of the RFIC since 2000. During his career, he has published almost 120 refereed journal papers and 355 refereed conference papers. Prof. Kim has been issued more than 40 patents.