Dual- and Triple-Mode Branch-Line Ring Resonators and Harmonic Suppressed Half-Ring Resonators

Choon Sik Cho, *Member, IEEE*, Jae W. Lee, *Member, IEEE*, and Jaeheung Kim, *Member, IEEE*

***Abstract*—Ring resonators have been widely used for various applications. Dual-mode ring resonators have also been investigated due to their applicability to multifrequency mode requirement. In this paper, dual-mode ring resonators using a branch line are designed along with a systematic approach. Triple-mode branch-line ring resonators are also designed adding two branch lines to the ring resonator. Adding more branch lines, multimode resonators can be realized based on the design procedure developed here. The location of the branch lines determines the additional resonant frequencies other than the fundamental resonant frequency generated by the enclosing ring. Furthermore, half-ring resonators working at 2.5 GHz are proposed for suppressing multiple harmonics (second and third harmonics) and providing size reduction with employment of various physical configurations. Equalizing the even- and odd-mode phase delays, harmonics are suppressed effectively in the design of half-ring resonators. Double half-ring resonators with a long opening gap are investigated to continuously decrease the resonant frequency. An open-loop structure provides flexible design and lowers the resonant frequency. Two dual-mode ring resonators and one triple-mode ring resonator are simulated and fabricated along with three different half-ring resonators.**

***Index Terms*—Dual-mode ring resonators, half-ring resonators, harmonic suppression, triple-mode ring resonators.**

I. Introduction

MICROSTRIP ring resonators have been widely used for the measurement of effective dielectric constants, dispersion, discontinuity parameters, and phase velocity, as well as the determination of optimum substrate thickness [1]–[4]. They also constitute important building blocks for filters [5], oscillators [6], and antennas since they show compactness in size, low radiation loss, high quality factor, easy fabrication, and freedom from open end effects. Much effort has been devoted to the design of bandpass filters and oscillators using the advantage of ring-resonator topology. The ring resonators have been investigated both in theoretical and experimental points-of-view [7]. Various physical configurations have been introduced, studied, and validated [8]. The difference between open and closed loops also results in a different frequency response of the resonators [9]. Sometimes the shape of the main resonators has been modified to achieve better performance in terms of frequency response, quality factor, size reduction, design flexibility, and so on. Since the modern wireless communication systems require multiple frequency bands for their operation, dual-mode ring resonators have been widely studied. Orthogonal excitation and perturbation have been generally utilized in the middle of the ring to create the different degenerate modes [4], [10]. However, the physical realization for the perturbed section was ambiguously determined using repeated simulation. Hence, this approach demands a time-consuming task to obtain the desired physical layout. Various efforts have been made to maintain the different even- and odd-mode resonant frequencies [11]–[14]. These also provide a complicated approach to the calculation of necessary physical dimension. In this study, branch lines are simply added to generate more resonant frequencies in the very accurate manner for the desired system requirements. Moving the location of the branch lines controls the second resonant frequency $(2f_0)$ since the branch line works as an additional resonator. One branch is simply added for the dual-mode operation since the enclosing ring already provides a resonant frequency (f_0). For the triple-mode resonator, two branches are added. Using this approach, multiple-mode resonators can easily be realized by adding more branches similarly to the dual- and triple-mode resonators.

In the meantime, linearity has been of prime interest for the current wireless communication systems employing multiple channels within a narrow frequency band compared to the past systems. Since active microwave circuits have inherently nonlinearity, it is a sometimes cumbersome task to increase linearity without the help of passive circuits around them. When the ring resonators are used for bandpass filters cascaded with active circuits, the ring resonator can play a significant role in alleviating the nonlinearity problems with a suppression of harmonics. Since the second and third harmonics affect the linearity performance dominantly in frequency response, double half-ring resonators are proposed in this paper. Since the difference of even- and odd-mode phase delay brings about the harmonic at $2f_0$ such as presented in the coupler design [14], we analyze novel double half-ring resonators as designed in [15] based on the systematic approach to suppress harmonics. Two half-ring resonators are cascaded through a long opening side gap for equalization of the equal even- and odd-mode phase delay, which finally provides a high-Q resonance.

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C. S. Cho and J. W. Lee are with the School of Electronics, Telecommunication and Computer Engineering, Hankuk Aviation University, Goyang 412-791, Korea (e-mail: cscho@hau.ac.kr; jwlee1@hau.ac.kr).

J. Kim is with the Intelligent Radio Engineering Center, Information and Communications University, Daejeon 305-732, Korea (e-mail: jaeheung@icu.ac.kr).

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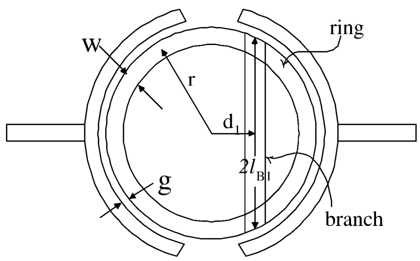


Fig. 1. Dual-mode branch-line ring resonator.

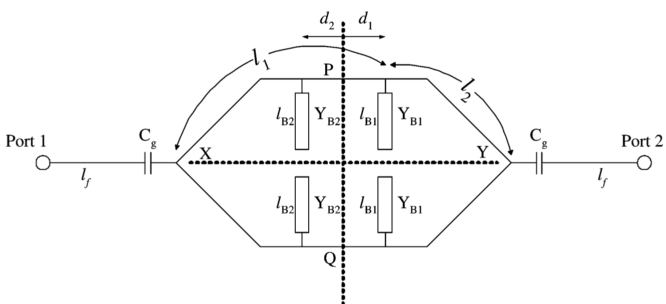


Fig. 2. Equivalent transmission-line circuit for the dual- and triple-mode branch-line ring resonator.

II. Dual- and Triple-Mode Branch-Line Ring Resonators

A. Dual-Mode Branch-Line Ring Resonators

According to the conventional design of the ring resonators [7]–[9], the ring resonators create the resonance based on the radius r of the ring as follows in (1):

$$2\pi r = n\lambda_g \tag{1}$$

where $n = 1, 2, 3, \ldots$, and λ_g is the guide wavelength at the resonance. The ring resonator can produce only one fundamental resonant frequency because both the even- and odd-mode excitations have the same half-wavelength transmission-line resonator (open circuit for the even mode and short circuit for the odd mode) [16]. For dual-mode ring resonators, orthogonal excitation topology using various perturbations has been utilized [17], [18]. However, since the input and output ports are located closely, the coupling between the input and output ports can occur.

A dual-mode ring resonator in which the input and output ports are oppositely positioned 180° out-of-phase employing a bridging branch line is proposed as shown in Fig. 1. The resonance condition as follows in (2) for the ring resonator can be applied here to the branch-line ring resonator using the equivalent transmission line circuit with a single branch (B_1), as in Fig. 2:

$$Y_1 + Y_2 = 0 \tag{2}$$

where Y_1 is the admittance looking into the upper path and Y_2 is the admittance looking into the lower path at the XY-plane, as in Fig. 2. Without branch lines, the resonance is determined by even- and odd-mode excitation at the PQ-plane. Adding a branch line, the ring can be divided into two half rings for analysis at the plane offsetting from PQ for even- and odd-mode excitation. This lowers the fundamental resonant frequency slightly. The dual- and triple-mode ring resonators are modeled by an equivalent circuit, as in Fig. 2, where the branch line B_2 is applied for the triple-mode resonator, and is equalized to an open stub with the length $l_{B1}/2$ due to the same potential that occurred at two end points of the branch line. The length of the feed line l_f is suitably chosen for convenient feeding, and the gap capacitance C_g is replaced by a microstrip-line gap for easy fabrication.

The admittance of the branch line B_1, as in (3), is composed of the combination of a T-junction and an open-stub with length $l_{B1}/2$. This gives rise to additional resonance for dual-mode operation

$$Y_{B1} = Y_0 \tanh(\gamma l_{B1}/2) + jB_T \tag{3}$$

where B_T represents the admittance for the T-junction between the enclosed ring and branch line.

The additional resonant frequency by a branch line is controlled by the offset d_1. Therefore, two resonant frequencies created by the enclosing ring and branch line comprise the dual-mode resonator. For the simplicity of fabrication and insertion loss, g and θ have been chosen as small and realizable as possible. In this study, $g = 0.5$ mm and $\theta = 30^\circ$ were used.

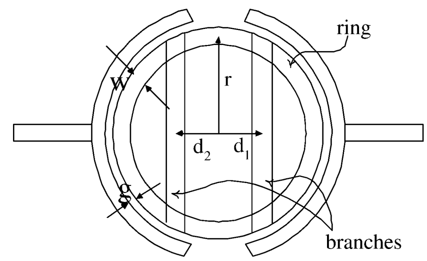


Fig. 3. Triple-mode branch-line ring resonator.

B. Triple-Mode Branch-Line Ring Resonators

Two branch lines (B_1 and B_2 in Fig. 2) are added slightly asymmetrically to the ring resonator for the triple-mode operation, as in Fig. 3. Using the design principle derived in Section I, one additional branch line, i.e., B_2 in Fig. 1, is added based on the desired resonant frequency. If the mutual coupling between the branch lines is ignorantly small, multiple mode more than triple mode can also be realized. In this study, a triple-mode resonator is designed by varying $d_1 + d_2 (= d)$.

III. Half-Ring Resonators

If the even- and odd-mode phase velocities of the ring resonators are different, harmonics are generated [13], [14]. Unless $d_1 = 0$ in Fig. 1, the dual-mode ring resonator shows harmonics growing in the frequency response. Also in Fig. 3, harmonics grow as the condition $d_1 = d_2$ is not maintained. Moreover, current microwave systems require fundamental resonant frequency with a high-Q factor. Since the general ring resonators

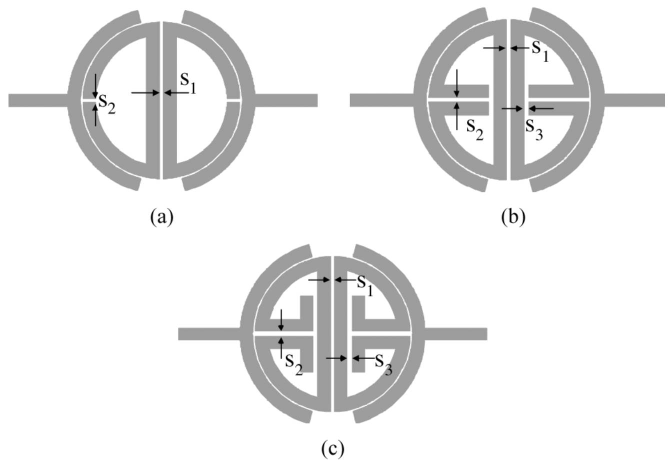


Fig. 4. Configurations of the half-ring resonators. (a) Open-loop half-ring resonators. (b) Open-loop half-ring resonator with open stubs. (c) Open-loop half-ring resonator with bent open stubs.

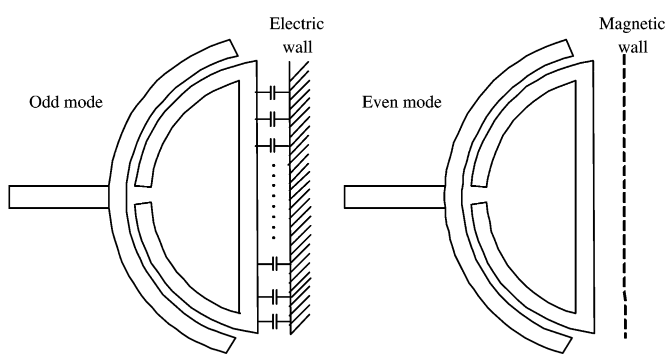


Fig. 5. Equivalent transmission-line circuit for half-ring resonators.

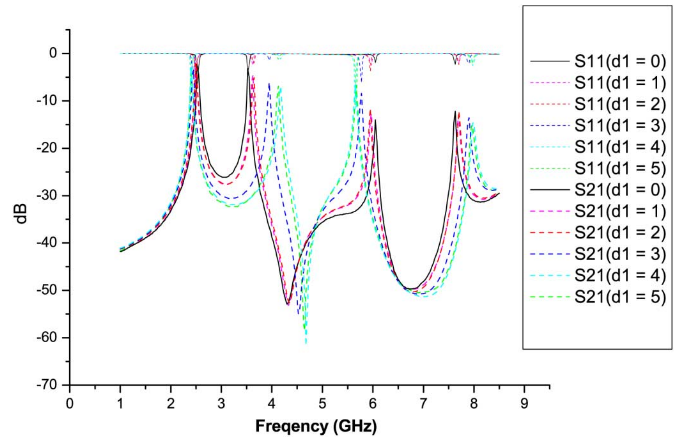


Fig. 6. Simulated return losses and insertion losses for dual-mode ring resonators.

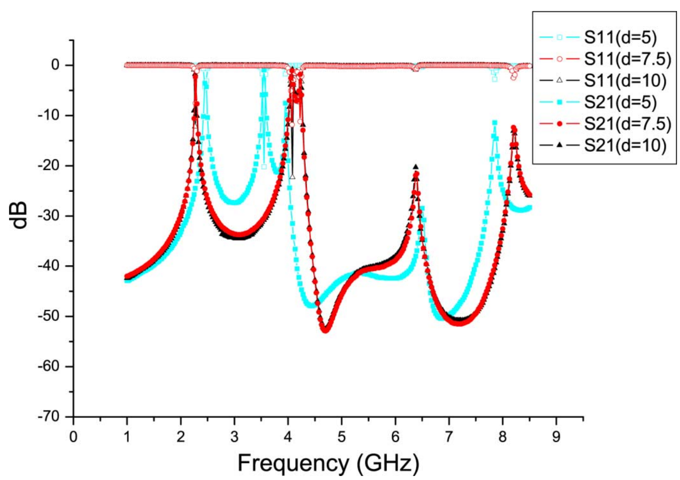


Fig. 7. Simulated return losses and insertion losses for triple-mode ring resonators.

show a low-Q factor and multiple harmonics, some perturbation is needed to obtain a high-Q factor and suppression of harmonics.

To alleviate harmonics, phase velocities for the even and odd modes have to be equal, For this, capacitors are sometimes added to extend the traveling path of the odd mode [11]–[14]. Since Fig. 4 can be split into the equivalent circuits for the even and odd modes, as in Fig. 5 [4], additional capacitance between the vertical conductor and virtual ground for the odd mode is generated, thus lengthening the phase delay of the odd mode. Multiple harmonics can be reduced effectively varying S_1 in Fig. 4. In addition, the resonant frequency is continuously lowered by increasing the whole length of open half-ring resonators, as shown in Fig. 4(b) and (c). The spacing S_2 and S_3 also affect the frequency response of the half-ring resonator; in this study, 1 mm has been chosen for easy fabrication.

IV. Simulation

Based on the design philosophy developed in Section I, dual-mode branch-line ring resonators have been designed using a branch with various offsets (d_1) and simulated as shown in Fig. 6. As the offset d_1 is increased, the second resonant frequency generated from the branch line is decreased, as expected. Furthermore, harmonics are effectively suppressed using this branch line.

For the triple-mode branch-line ring resonator, two branches are added corresponding to the design methodology established in Section II-B. In this study, d_1 and d_2 are adjusted very similarly to realize the similar second and third resonant frequencies other than the first resonant frequency caused by the enclosing ring. For simplicity, $d_1 + d_2 = 5$ mm, 7.5 mm, and 10 mm have been simulated with maintaining $d_1 - d_2 = 0.2$ mm. Fig. 7 shows the simulated performance for the triple-mode ring resonators. The first resonance is created by the enclosing ring, which can be observed in the dual-mode ring resonator. The second and third resonances occur according to d_1 and d_2, respectively. Similar to the dual-mode resonator, the first resonant frequency is lowered as the branch lines are apart. The increased mutual coupling between the enclosing ring and the branch lines makes the first resonant frequency to shift (or lower) a bit. Choosing d_1 and d_2 appropriately, harmonics are suppressed in the design of the triple-mode branch-line ring resonators.

For the last case of the resonators, two half-ring resonators are cascaded through a long side gap to create a single resonant frequency and suppress the harmonics effectively. As shown in Fig. 8, three different designs have been examined by continu-

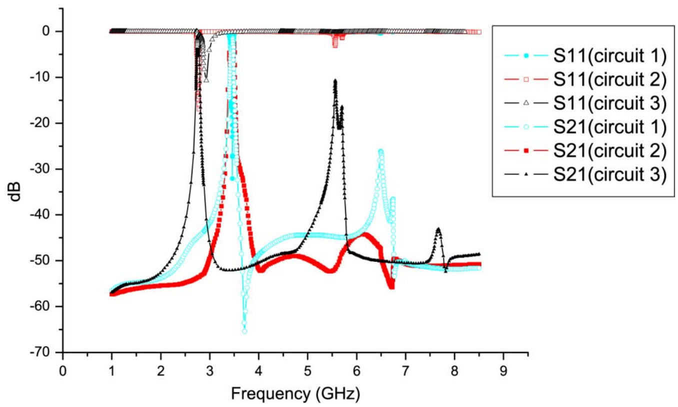


Fig. 8. Simulated return losses and insertion losses for half-ring resonators.

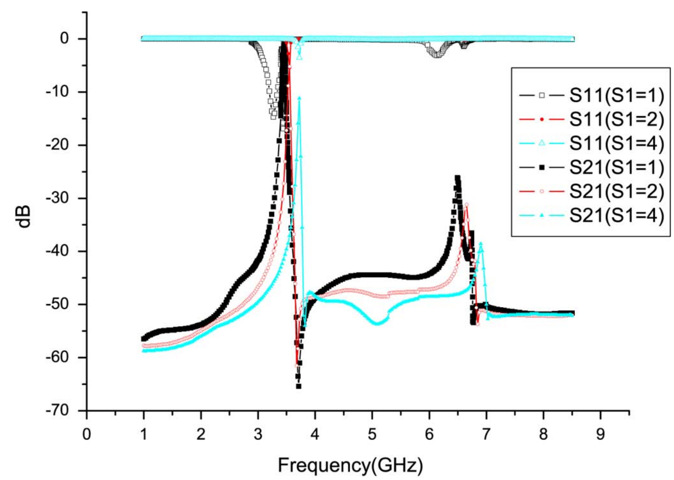
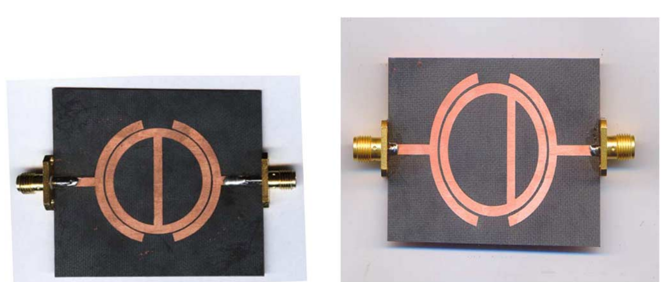


Fig. 9. Simulated return losses and insertion losses for half-ring resonators in terms of S_1.



(a) (b)

Fig. 10. Fabricated dual-mode ring resonators. (a) $d_1 = 0$. (b) $d_1 = 5$ mm.

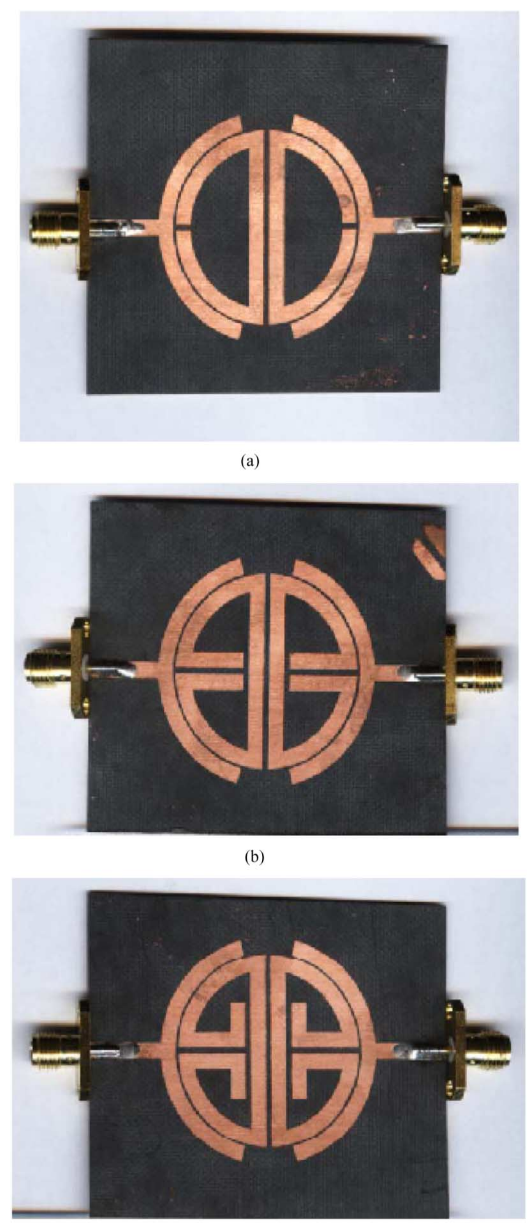
ously increasing the whole length of the half-ring with an open stub or open bent stub. For obtaining resonance at 2.5 GHz, the length and gap of the open stub is appropriately tuned.

To optimize the dimension of a long side gap, S_1 has been varied using 1, 2, and 4 mm, as in Fig. 9. Due to lower insertion loss and closer modal phase velocities for final fabrication, 1 mm has been chosen for S_1.

V. Fabrication and Measurement

Various ring resonators were fabricated for verification of the proposed design methodology on a Duroid/RT5880 substrate with a dielectric constant 2.2 and a height 0.787 mm, as shown in Figs. 10–12. $w = 2.4$ mm, $r = 13.93$ mm, $g = 0.5$ mm, $l_f = 15$ mm, $\theta = 30°, S_2 = 1$ mm, and $S_3 = 1$ mm have been used for all design of ring resonators. Two circuits

Fig. 11. Fabricated triple-mode ring resonators ($d_1 = 4.9$ mm, $d_2 = 5.1$ mm).



(a)

(b)

(c)

Fig. 12. Fabricated half-ring resonators. (a) Circuit 1. (b) Circuit 2. (c) Circuit 3.

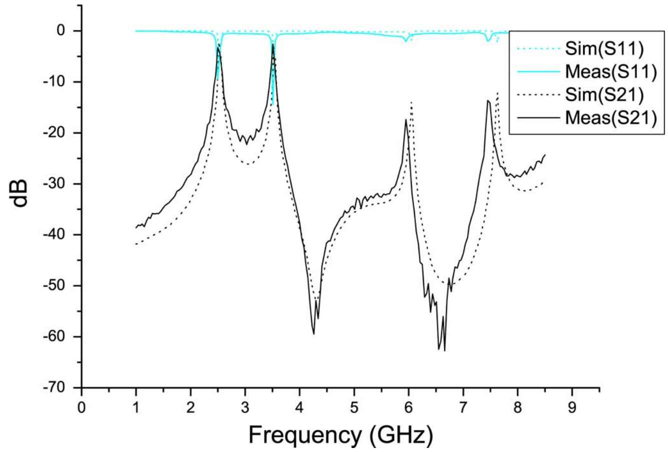


Fig. 13. Measured and simulated return and insertion losses for dual-mode ring resonators ($d_1 = 0$).

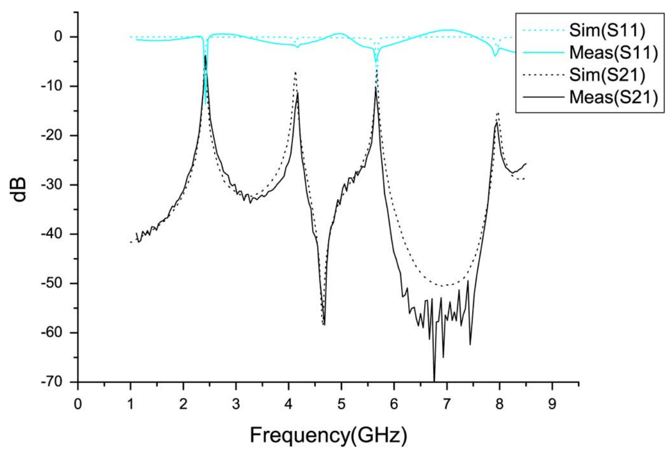


Fig. 14. Measured and simulated return and insertion losses for dual-mode ring resonators ($d_1 = 5$ mm).

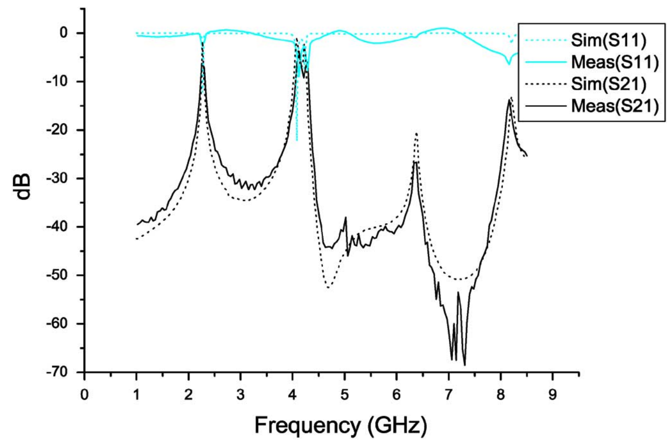


Fig. 15. Measured and simulated return and insertion losses for triple-mode ring resonator ($d_1 = 4.9$ mm, $d_2 = 5.1$ mm).

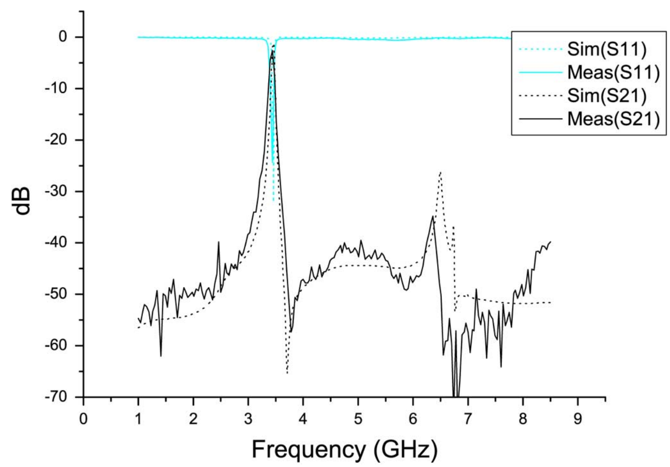


Fig. 16. Measured and simulated return and insertion losses for cascaded half-ring ring resonator (circuit 1).

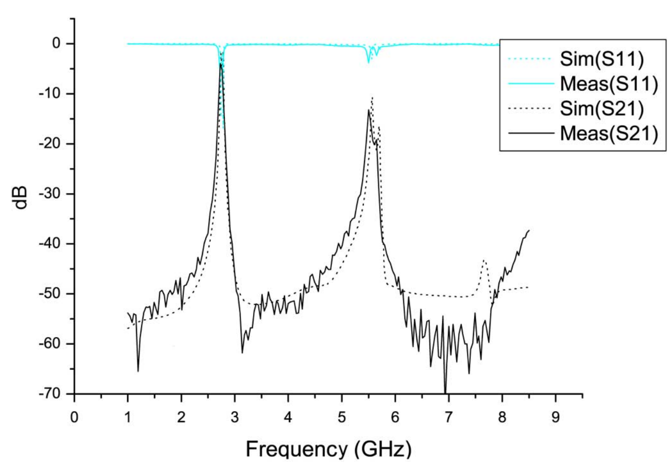


Fig. 17. Measured and simulated return and insertion losses for cascaded half-ring ring resonator (circuit 2).

of dual-mode branch-line ring resonators were fabricated by varying the distance d_1 ($d_1 = 0$ and 5 mm). As expected, the symmetrical dual-mode branch-line ring resonator suppresses the harmonics more effectively; however, the asymmetrical resonator suppresses the harmonics less. The resonant frequencies are observed as 2.5/3.51 GHz and 2.42/4.17 GHz for $d_1 = 0$ and $d_1 = 5$ mm, respectively, as shown in Figs. 13 and 14. One circuit of the triple-mode resonator for $d_1 = 4.9$ mm and $d_2 = 5.1$ mm was fabricated using the layout obtained in Section IV. As shown in Fig. 15, three resonant frequencies, i.e., 2.25/4.12/4.29 GHz, are obtained. The harmonics are suppressed considerably because of close modal phase velocities and phase delays. Simulated and measured results are in good agreement.

Three circuits of half-ring resonators are fabricated based on the layouts that appeared in Section III. Figs. 16–18 shows measurement results for the harmonic suppressed half-ring resonators. As the whole length of the half-ring increases, the single resonant frequency decreases and finally reaches 2.45 GHz. Second and third harmonics are successfully suppressed for this cascaded half-ring resonators. Simulated and measured results are also in good agreement.

Q factors of the all resonators designed in this study are shown in Table I. Dual-mode ring resonators represent a higher Q factor compared to triple-mode ring resonators since the electromagnetic energies are distributed at more resonant frequencies in the triple-mode operation. Resonant frequencies and insertion losses are also summarized in Table I for comparison between three different topologies of the ring resonators.

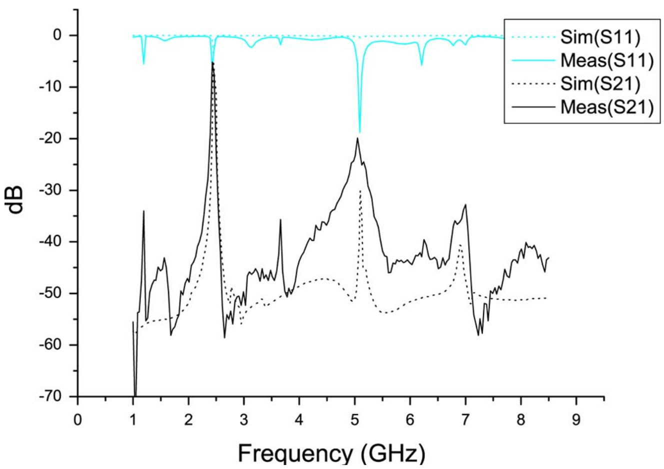


Fig. 18. Measured and simulated return and insertion losses for cascaded half-ring ring resonator (circuit 3).

TABLE I
SUMMARY OF MEASURED RESULTS

		f_0 (GHz)	Insertion Loss (dB)	Q-factor
Dual-mode	$d_1 = 0$	2.5	-3.27	58
		3.51	-2.6	62
	$d_1 = 5$ mm	2.42	-3.75	61
		4.17	-11.3	60
Triple-mode	$d_1 = 4.9$ mm	2.25	-6.29	25
	$d_2 = 5.1$ mm	4.12	-3.77	46
		4.29	-6.07	48
Half-ring	Circuit 1	3.43	-2.73	88
	Circuit 2	2.78	-4.43	66
	Circuit 3	2.45	-4.9	61

VI. CONCLUSION

Dual-mode ring resonators were designed, simulated, and measured using the systematic approach developed in this study. A branch line bridging the enclosing ring creates one additional resonance other than the fundamental resonance caused by the ring. The location of the branch line, in other words, variation of the length of the branch line, determines the second resonance of the dual-mode ring resonator. Therefore, a systematic design method can possibly expect the accurate resonant frequencies of dual-mode resonators. A symmetric configuration of the dual-mode resonator suppresses the harmonics more effectively due to the equal phase delays of the even and odd modes. Simulated and measured results are in a good agreement with each other.

Triple-mode ring resonators were similarly designed to the dual-mode ring resonators adding one more branch line by bridging the enclosing ring. Varying the location of the branch lines effectively controls the second and third resonant frequencies. However, due to the mutual coupling between the branch lines and/or the branch line and the enclosing ring, the first resonant frequency is slightly lowered and the additional resonances are also affected. Harmonic suppression is also obtained by using almost symmetric configuration. The measured result shows a good agreement with the simulated result expected by a systematic design approach.

Single resonance and a considerable amount of harmonic suppression are obtained by employing a cascaded half-ring resonator configuration. Due to extended phase delay of the odd-mode excitation, harmonics are successfully reduced and single resonant frequency is obtained easily. Excellent agreement between the simulated and measured results shows that the design method developed in this study is fully applicable to any other design for suppressing the harmonics and controlling the number of resonant frequencies.

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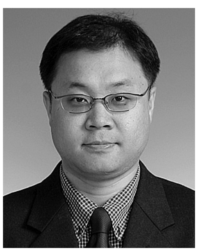
Choon Sik Cho (S'98–M'99) received the B.S. degree in control and instrumentation engineering from Seoul National University, Seoul, Korea, in 1987, the M.S. degree in electrical and computer engineering from the University of South Carolina, Columbia, in 1995, and the Ph.D. degree in electrical and computer engineering from University of Colorado at Boulder, in 1998.

From 1987 to 1992, he was with LG Electronics, where he was involved with communication systems. From 1999 to 2003, he was with Pantec&Curitel, where he was principally involved with the development of mobile phones. In 2004, he joined the School of Electronics, Telecommunication and Computer Engineering, Hankuk Aviation University, Goyang, Korea. His research interests include the design of RF integrated circuits (RFICs)/monolithic microwave integrated circuit (MMICs), especially for power amplifiers, oscillators, low-noise amplifiers (LNAs), antennas and passive circuit design, and the computational analysis of electromagnetics.



Jae W. Lee (S'92–M'98) received the B.S. degree in electronic engineering from Hanyang University, Seoul, Korea, in 1992, and the M.S. and Ph.D. degrees in electrical engineering (with an emphasis in electromagnetics) from the Korea Advanced Institute of Science and Technology (KAIST), Daejon, Korea, in 1994, and 1998, respectively.

From 1998 to 2004, he was a Senior Member with the Advanced Radio Technology Department, Radio and Broadcasting Research Laboratory, Electronics and Telecommunications Research Institute (ETRI), Taejon, Korea. He then joined the School of Electronics, Telecommunication and Computer Engineering, Hankuk Aviation University, Goyang, Korea, where he is currently an Assistant Professor. His research interests include high power-amplifier design, computational electromagnetics, electromagnetic interference (EMI)/electromagnetic compatibility (EMC) analysis on printed circuit boards (PCBs), and component design in microwaves and millimeter waves.

Jaeheung Kim (S'98–M'02) received the B.S. degree in electronic engineering from Yonsei University, Seoul, Korea, in 1989, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Colorado at Boulder, in 1998 and 2002, respectively.

From 1992 to 1995, he was with the DACOM Corporation, where he was involved with wireless communication systems. From 2002 to 2006, he was with the Department of Electrical and Electronic Engineering, Kangwon National University, Choonchun, Korea. In 2006, he joined the Intelligent Radio Engineering Center, Information and Communications University, Daejeon, Korea. His research interests include beam-forming arrays and high-efficiency active circuits.