Bandpass Filters using T-shape Stepped Impedance Resonators for Wide Harmonics Suppression and their Application for a Diplexer

Reungyot Lerdwanittip, Apirada Namsang, and Prayoot Akkaraekthalin

Abstract—In this paper, the T-shape stepped impedance resonators are adopted for the design of microstrip bandpass filters for wide harmonics suppression. The proposed filters are operated at the center frequency of 2.44 GHz and 5.20 GHz, respectively. These bandpass filters have been also applied for a high performance diplexer. The insertion losses at the center frequencies of 2.44 and 5.20 GHz are 1.23 and 1.18, respectively. The applicable return losses for both frequency bands and a wide stopband better than 17 dB up to 20 GHz have been obtained.

Index Terms—Bandpass filter, diplexer, T-shape stepped impedance resonator, harmonics suppression

I. INTRODUCTION

Broadband wireless access communication systems are rapidly expanding market. The channel separator systems commonly employ filters and diplexers in microwave and mm-wave transceivers. Planar filters are particularly popular structures because they can be fabricated by using printed circuit technology suitable for commercial applications due to their compact size and low-cost integration [1]. Microstrip bandpass filters can be easily mounted on a dielectric substrate and can provide more flexible design of the circuit layout. For the planar filter design, it is necessary to select proper resonator types since they are the basic required components of the filter. To reduce the resonator size, U-shaped hairpin resonator is proposed in [2-3], but it has some unwanted signal nearly the center frequency. The half-wavelength parallel-coupled microstrip filter may be influenced by the spurious response at the 2f0, twice the passband frequency, which it reduces the attenuation of the stopband and affects the symmetry of the passband [4]. The quarter-wavelength resonator filters have the first spurious response at the 3f0, but they require short-circuit connections with via holes, which are not quite compatible with planar fabrication techniques [5, 6]. In order to overcome these drawbacks, the inverted microstrip combining different stepped impedance resonators with a specified coupling angle are presented in designing the bandpass filters [7, 8]. In case of the harmonics problem, there are many methods that have been proposed to solve this problem [9, 10]. The asymmetrical structure can be also used to suppress the harmonic responses [11]. The microstrip resonator with the hook feed lines is a good structure for harmonic suppression [12].

In this paper, T-shape stepped impedance resonators are proposed to be a main part of the bandpass filters. The T-shape stepped impedance resonator structure may result in the first spurious response at 3f0, but it can be suppressed by using a bent resonator and hook feed lines. The designed diplexer is based on combination of two proposed bandpass filters. The measured result of the diplexer is in a good agreement with the simulated predictions, which has a wideband harmonic suppression.
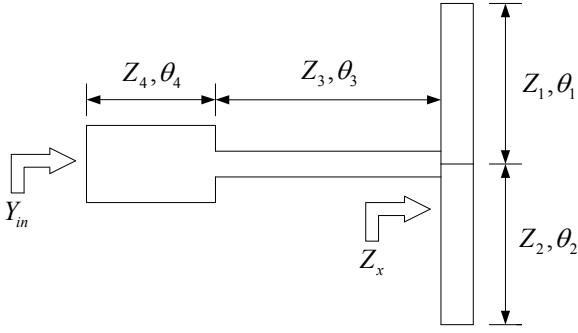
Fig. 1. The structure of T-shape stepped impedance resonator.

II. 2.4 GHz Bandpass Filter

The proposed bandpass filter is designed with basic structure T-shape stepped impedance resonator as shown in Fig. 1. It consists of the four segments which their characteristic impedances are Z_1, Z_2, Z_3, and Z_4, corresponding to their electrical lengths of θ_1, θ_2, θ_3, and θ_4, respectively.

The input impedance of each resonator can be analyzed by the basic transmission line which is:

$$Z = Z_0 \frac{Z_L + j Z_0 \tan \beta \ell}{Z_0 + j Z_L \tan \beta \ell} \tag{1}$$

The high impedance sections of Z_1, θ_1 and Z_2, θ_2 can be analyzed with the open circuit transmission line:

$$Z = -j Z_0 \cot \beta \ell \tag{2}$$

From Eq. (2), the impedance of the cascade of two high impedance sections is $-jZ_x$, which Z_x is

$$Z_x = \frac{Z_1 Z_2 \cot \theta_1 \cot \theta_2}{Z_1 \cot \theta_1 + Z_2 \cot \theta_2} \tag{3}$$

So that, the input admittance (Y_{in}) that is looking from left hand side of the T-shape stepped impedance resonator is related by Eq. (1) and Eq. (3) as following:

$$Y_{in} = \frac{Z_3 Z_4 + Z_4 Z_x \tan \theta_3 + Z_3 Z_x \tan \theta_4 - Z_3^2 \tan \theta_3 \tan \theta_4}{j \left[Z_3^2 \tan \theta_3 + Z_3 Z_4^2 \tan \theta_4 + Z_4 Z_x \tan \theta_3 \tan \theta_4 - Z_3 Z_4 Z_x \right]} \tag{4}$$

At the resonance condition, $Y_{in} = 0$, so that the resonance can be written as:

$$\frac{Z_3 \tan \theta_3 \tan \theta_4}{Z_4} - \frac{Z_x \tan \theta_3}{Z_3} - \frac{Z_x \tan \theta_4}{Z_4} = 1 \tag{5}$$

From the formula Eq. (5), it can be found that the impedances and the electrical lengths for the desired frequencies can be easy to solve when choosing the value of impedance Z_1 equal Z_2 and the electrical length θ_1 equal to θ_2. This bandpass filter is designed on the substrate with the relative dielectric constant of 3.38, the loss tangent of 0.002, and the thickness of 0.8 mm. The operating frequency of 2.44 GHz is chosen to be the fundamental resonant frequency of the first proposed bandpass filter. From the calculation method, the parameters are not exactly equal to the desired frequency, so that the optimization should be required. However, the results from calculation using Eq. (5) have been used as initial parameters. By the optimization, with the electromagnetic software IE3D [13], the physical parameters can be converted to the impedances and the electrical lengths at the center frequency. So their resulting of the T-shape stepped impedance resonator impedances are $Z_1 = 81.88$ Ω, $Z_2 = 81.88$ Ω, $Z_3 = 117.76$ Ω, and $Z_4 = 46.08$ Ω, corresponding to their electrical lengths of $\theta_1 = 42.34°$, $\theta_2 = 42.34°$, $\theta_3 = 55.65°$ and $\theta_4 = 25.26°$, respectively. The resonance response of the T-shape stepped impedance resonator is shown in Fig. 2. The center frequency is showed at 2.44 GHz and the first harmonic is shown at 7.27 GHz or around $3f_0$. It is noticed that the harmonic
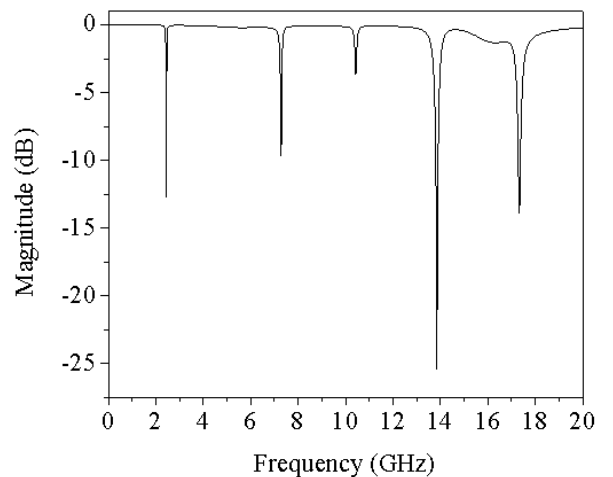

Fig. 2. The T-shape stepped impedance resonator response (S_{11}).

responses are also produced around 10.70, 13.85 and 17.32 GHz. In same way, the simulator is used to discover the characteristic of the coupling coefficient of the two resonators. The coupling coefficient can be found by the equation as [14]:

$$\text{Coupling coefficient} = \pm \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \qquad (6)$$

where f_1 and f_2 are the extracting of the even- and odd-mode resonance frequencies.

The high impedance segment of the resonators have been bent and coupled which act as the folded resonators as shown in Fig. 3, resulting in harmonics response is suppressed around $3f_0$ [12]. Fig. 4 showed the value of coupling coefficient versus distance of two resonators which are followed by the Eq. (6). Also, with optimized internal coupling between resonators, the lower insertion loss can be obtained. Fig. 5 shows the simulated results of the T-shape stepped impedance resonator bandpass filter, which is still being on the resonance frequency, but the harmonic signal, the unwanted signal, is generated at 10.70 GHz, around the forth harmonic of the center frequency. So the method to resolve this problem is interested. The hook feed line has been proposed for
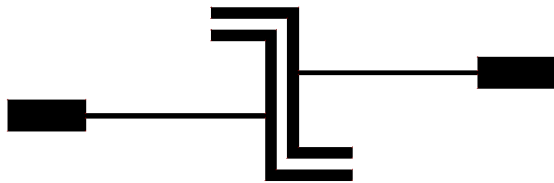
suppressing the unwanted signals, which it can be described by the odd- and even-modes. The IE3D has been employed to evaluate the characteristics of the hook feed line by using the differential two-port model for two mode excitations as shown in Fig. 6. The frequency notch responses of the odd- and even-mode characteristics are produced around 10.54 and 10.89 GHz, as shown in Fig. 7.

Fig. 5. The simulated results of the T-shape stepped impedance resonator bandpass filter.

(a)

(b)

Fig. 6. The hook feed lines forming modeled. (a) Odd-mode, (b) Even-mode.

Fig. 3. The folded T-shape stepped impedance resonators bandpass filter with direct feed lines structure.

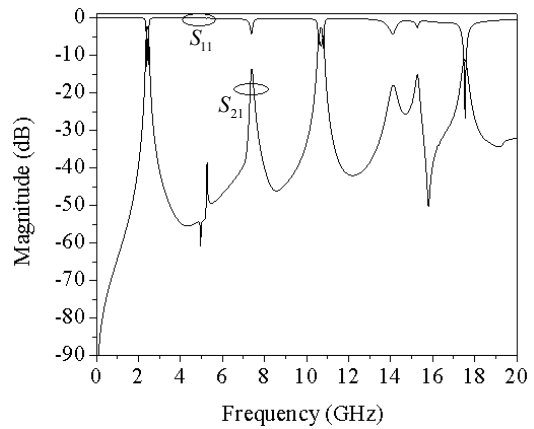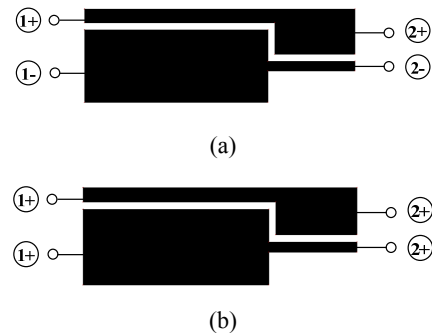**Fig. 4.** The coupling coefficient versus the distance between two coupled resonators of the bandpass filter.
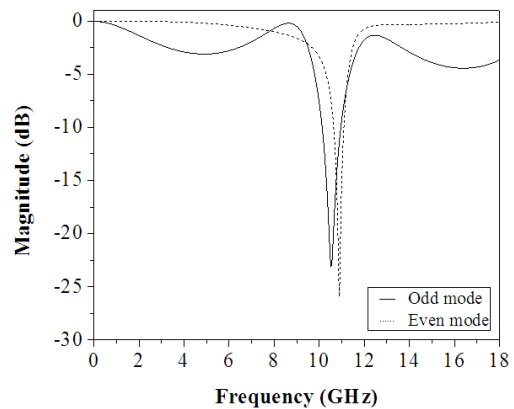

Fig. 7. Frequency responses (S_{21}) of the asymmetrical parallel coupled line with odd and even-mode excitations.

These odd- and even-mode responses will certainly affect the resonators, resulting in bandstop characteristic. Therefore the superior suppression of the forth harmonics can be obtained. The current distribution of the proposed bandpass filter with hook feed line at 10.70 GHz is shown in Fig. 8, which it can be explained that the the hook feed line acts as the notch filter to suppress the unwanted signal. As we can see that the unwanted signal (red color) is stopped at the beginning of the hook feed. The dimension of the hook feed line is acquired by the varying of the width and length of hook segment. It can be described that the suitable capacitance between the hook feed and the resonator section, Z_3, results in the stopband at 10.70 GHz. By the same way, it can also be explained with the odd-and even-mode characteristic for suppressing harmonics signals as described above.

The bandpass filter structure with the T-shape stepped impedance resonators and the hook feed lines have been then proposed for wide harmonics suppression, as shown in Fig. 9. The dimensions of the proposed filter are following (unit in mm): L_1 = 8.33, L_2 = 4.36, L_3 = 6.36, L_4 = 4.11, L_5 = 9.56, L_6 = 2.28, L_7 = 0.40, G_1 = 0.75, G_2 = 0.20, W_1 = 0.75, W_2 = 1.30, W_3 = 0.30 and W_4 = 0.40. Fig. 10 shows the comparison of the simulated results of the bandpass filter by using the T-shape stepped impedance resonators with the direct feed lines in Fig. 3 and the hook feed lines in Fig. 9. It can clearly seen that the unwanted signal at about 10.70 GHz can be suppressed by using hook feed lines, resulting in a wide stopband. The simulated results show a good bandpass performance at the 2.44 GHz. The insertion loss and the
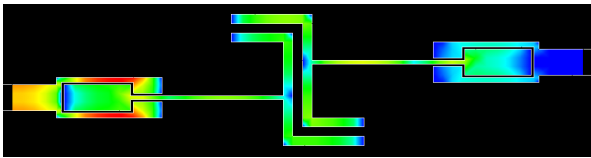

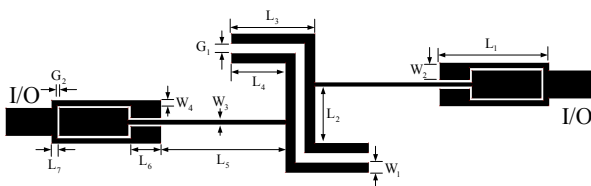**Fig. 8.** The current distribution of the bandpass filter with hook feed line at 10.70 GHz.

Fig. 9. The structure of the proposed filter at 2.44 GHz by using the T-shape stepped impedance resonators.
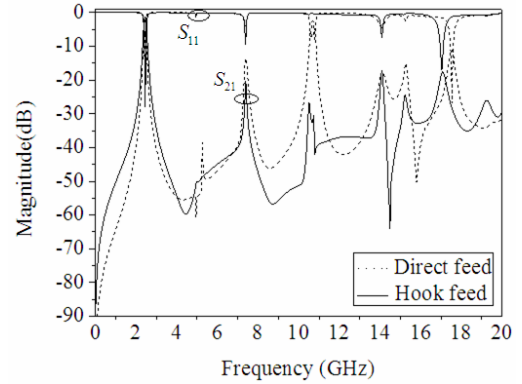

Fig. 10. Comparison the simulated results of bandpass filter 2.4 GHz using T-shape stepped impedance resonator with direct feed lines and the hook feed lines.

return loss are 1.31 dB and 28.93 dB, respectively. The proposed bandpss filter has wide stopband up to 20 GHz and the rejection level better than 20 dB.

III. 5.2 GHZ BANDPASS FILTER

From the T-shape basic structure as shown in Fig. 1 and according to the feeding method, they can be applied for the 5.20 GHz bandpass filter. The design is similar to the 2.44 GHz bandpass filter using the substrate with the relative dielectric constant of 3.38, the loss tangent of 0.002, and the thickness of 0.8 mm. From the calculation method, the parameters are not exactly equal to the desired frequency, so that the optimization should be required. However, the results from calculation using Eq. (5) have been used as initial parameters. By the optimization, with the electromagnetic software IE3D [13], the physical parameters can be converted to the impedances and the electrical lengths at the center frequency. The T-shape stepped impedances have been optimized, resulting in Z_1 = 81.88 Ω, Z_2 = 81.88 Ω, Z_3 = 117.76 Ω, and Z_4 = 46.08 Ω corresponding to their electrical lengths of θ_1 = 60.41°, θ_2 = 60.41°, θ_3 = 25.65°, and θ_4 = 44.60°, respectively as shown in Fig. 11(a).

As described above, the harmonics responses are generated around 14.50 GHz when using the direct feed lines. This harmonics signal is not necessary for applications of the bandpass filter. The hook feed lines can be used for resolved this problem to suppress the harmonic frequency for the bandpass filter of 5.20 GHz. The dimension of the hook feed line is acquired by the varying of the width and length of hook segment. It can

be described that the suitable capacitance between the hook feed and the resonator section, Z_3, results in the stopband at 14.50 GHz. By the same way, it can also be explained with the odd-and even-mode characteristic for suppressing harmonics signals as described above. The proposed structure is shown in Fig. 11(b). The dimensions of the filter are following (unit in mm): $L_1 = 6.33$, $L_2 = 2.81$, $L_3 = 4.83$, $L_4 = 2.92$, $L_5 = 1.18$, $L_6 = 2.65$, $L_7 = 0.40$, $G_1 = 0.41$, $G_2 = 0.20$, $W_1 = 0.75$, $W_2 = 1.30$ and $W_3 = 0.30$. So the comparisons of the direct feed lines and the hook feed lines on the T-shape stepped impedance resonators bandpass filter are shown in Fig. 12. It can be noticed that the harmonic frequency around 14.50 GHz can be suppressed and the high performance passband result is obtained at 5.20 GHz. The insertion and return loss are 0.58 and 52.62 dB, respectively.The proposed bandpss filter has a wide stopband up to 20 GHz and the
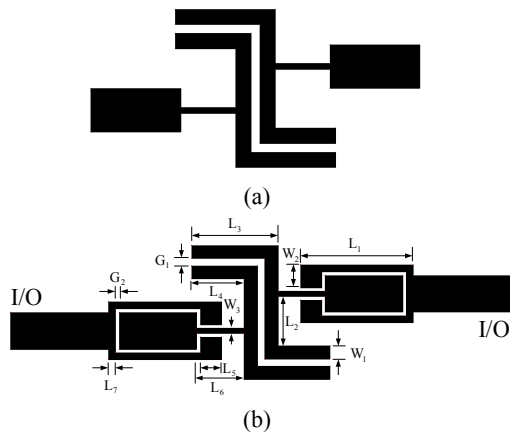
rejection level better than 20 dB.

IV. APPLICATION FOR DIPLEXER

As the excellent performance of the hook feed line which is combined with the T-shape stepped impedance resonator as described in the section II and III, for supporting the passband and wide stopband response, this method is suitable to apply for the diplexer application. The diplexer design is based on the T-shape stepped impedance resonator structure and the input and output ports with the hook feed lines for wide harmonics suppression. The design procedure begins with the design of two filters independently, which have already described in previous sections. The designed filters can be combined by using a T-junction. The junction lengths are around $\lambda/8$ at 2.44 GHz and $\lambda/2$ at 5.20 GHz. The T-junction is independent to both filters, so that the resonators can be adjusted separately corresponding to the resonance frequencies at 2.44 GHz and 5.20 GHz. The diplexer using T-shape stepped impedance resonator dimension is also designed on the Arlon25N substrate as shown in Fig. 13.

The dimensions of the proposed diplexer have been optimized by using IE3D, resulting in (unit in mm) $L_1 = 5.25$, $L_2 = 8.13$, $L_3 = 2.08$, $L_4 = 11.20$, $L_5 = 4.45$, $L_6 = 6.33$, $L_7 = 4.66$, $L_8 = 2.55$, $L_9 = 5.91$, $L_{10} = 6.61$, $L_{11} = 3.91$, $L_{12} = 11.80$, $L_{13} = 4.55$, $L_{14} = 5.42$, $L_{15} = 6.90$, $L_{16} = 4.59$, $L_{17} = 3.48$, $L_{18} = 5.25$, $L_{19} = 8.18$, $G_1 = 0.40$, $G_2 = 0.56$, $W_1 = 0.75$, $W_2 = 1.30$, $W_3 = 0.30$, and $W_4 = 0.75$. A photograph of the fabricated diplexer is shown in Fig. 14.

Fig. 11. The T-shape stepped impedance resonator-bandpass filter at frequency 5.20 GHz with (a) Direct feed lines, (b) Hook feed lines.
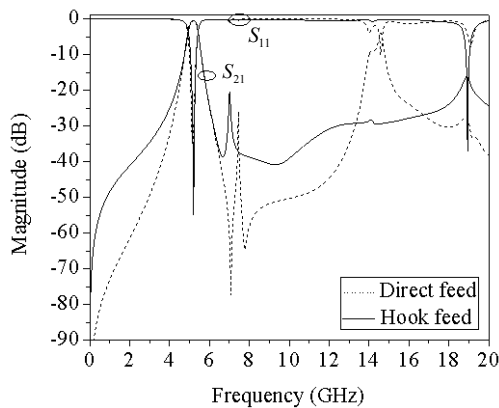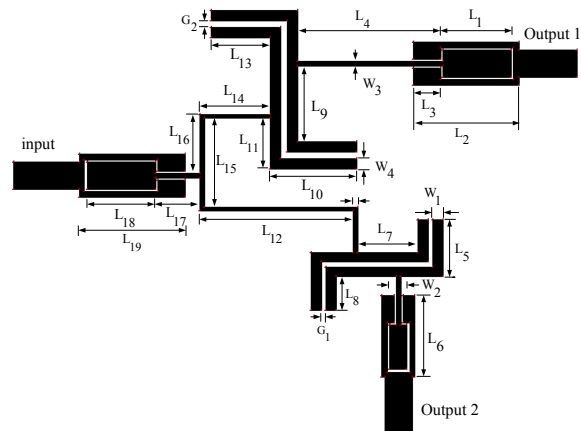

Fig. 12. Comparison the simulated results of bandpass filter 5.20 GHz using T-shape stepped impedance resonator with direct feed lines and the hook feed lines.

Fig. 13. The proposed diplexer using T-shape stepped impedance resonator.

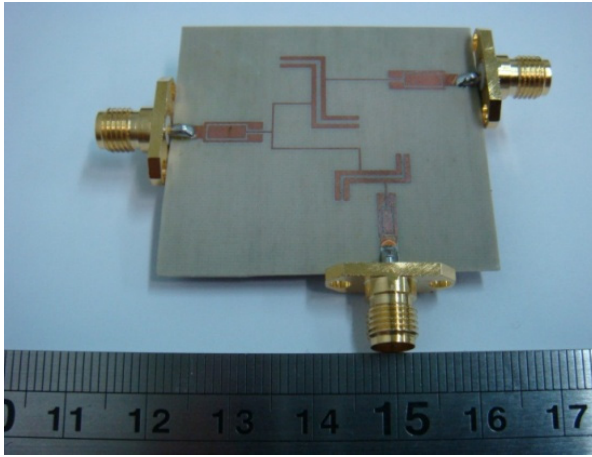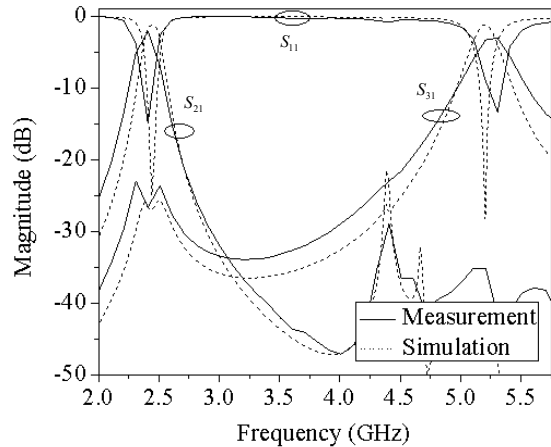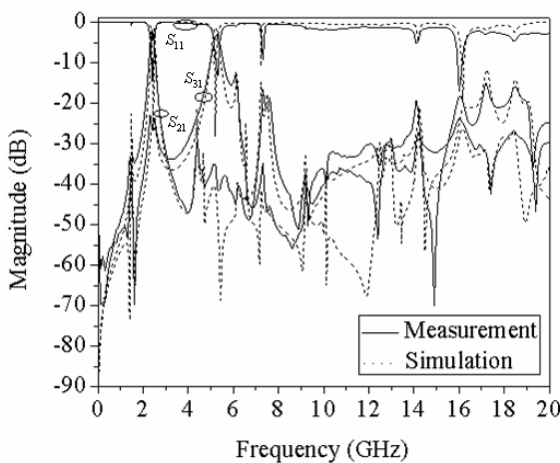Fig. 15(a) and (b) show the comparison of the simulated and measured results of the proposed diplexer in

Fig. 14. A photograph of the fabricated diplexer.

(a)

(b)

Fig. 15. Comparison of the simulated and measured results of diplexer with T-shape stepped impedance resonator. (a) Passband, (b) Wideband response.
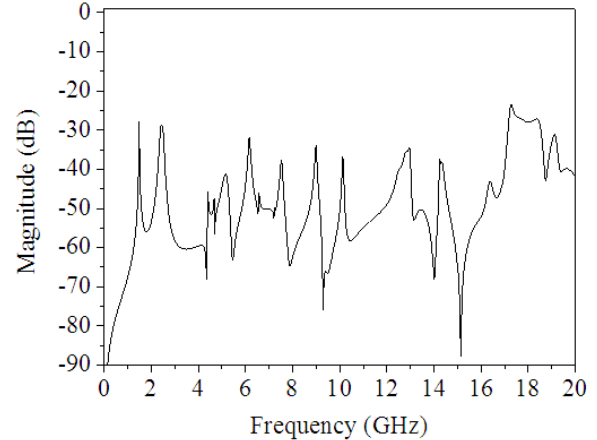

Fig. 16. The isolation of the proposed diplexer.

passband and wideband response, respectively. The measured results are in good agreement with the simulated prediction. From the measurement at the first band, the insertion and the return losses are 1.23 and 24.74 dB at the center frequency of 2.44 GHz. In another band, the insertion and the return losses are 1.18 and 30.26 dB, respectively. The isolation between two ports is greater than 30 dB up to $8f_0$, as shown in Fig. 16.

V. CONCLUSIONS

Bandpass filters using T-shape stepped impedance resonator have been proposed. The high performance bandpass filters for 2.44 and 5.20 bands with wide upper stopband have been obtained. The proposed filters combining with T-junction can be constructed to be a diplexer. The insertion losses are 1.23 dB and 1.18 dB at the center frequencies of 2.44 GHz and 5.20 GHz, respectively. The return losses are 24.74 dB and 30.26 dB at the center frequencies of 2.44 GHz and 5.20 GHz, respectively. The out-of-band rejection level of center frequencies of 2.44 GHz and 5.20 GHz are better than 17 dB and 25 dB, respectively. These proposed filters and diplexer can be further developed for smaller scale suitable for integrated circuit applications.

REFERENCES

[1] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998, ch8.

[2] E. G. Cristal and S. Frankel, "Hairpin-line and hybrid hairpin-line/half-wave parallel-coupled

filters," *IEEE Trans. Microw. Theory Tech.*, Vol. MTT-20, No.11, pp.719-728, Nov., 1972.

[3] G. L. Matthaei, N.O. Fenzi, R. J. Forse, and S. M. Rochlfing, "Hairpin comb filters for HTS and other narrowband applications," *IEEE Trans. Microw. Theory Tech.*, Vol.45, No.8, pp.1226-1231, Aug., 1997.

[4] S.B. Cohn, "parallel coupled transmission-line resonator filters," *IRE Trans. Microw. Theory Tech.*, vol. MTT-6, No.4, pp.223-231, Apr., 1958.

[5] Yu-Wei Chen, Yen-Ju Liu, and Min-Hua Ho, "The Quasi-elliptic Bandpass Filter Using Quarter-wavelength Stepped Impedance Resonators," *PIERS Online*, Vol.2, No.6, pp.605-608, 2006.

[6] C.-H. Lee, C.-I. G. Hsu, and L.-Y. Chen, "Band-notched ultra-wideband bandpass filter design using combined modified quarter-wavelength tri-section stepped-impedance resonator," *IET Microwaves Antennas & Propagation,* Vol.3, No.8, pp.1232-1236, 2009.

[7] B. Easter and K. A. Merza, "Parallel-coupled-line filters for inverted-microstrip and suspended substrate MIC's," in *11th Eur. Microwave Conf. Dig.*, 1981, pp.164-167.

[8] C. F. Chen, T. Y. Huang, and R. B. Wu, "Design of microstrip bandpass filters with multiorder spurious mode suppression," *IEEE Trans. Microw. Theory Tech*, Vol.53, No.12, pp.3788-3793, Dec., 2005.

[9] C. Quendo, E. Rius, C. Person, and M. Ney, "Integration of optimized low-pass filters in a bandpass filter for out-of-band improvement," *IEEE Trans. Microw. Theory Tech.*, Vol.49, pp.2376–2383, Dec., 2001.

[10] J.-T. Kuo and E. Shih, "Stepped impedance resonator bandpass filters with tunable transmission zeros and its application to wide stopband design," in *IEEE MTT-S Int. Microwave Symp. Dig,* pp.1613–1616, 2002.

[11] A. Namsang, T. Majaeng, J. Jantree, A. Chaimool and P. Akkaraekthalin, "Stepped-impedance hairpin resonators with asymmetric capacitively loaded coupled lines for improved stopband characteristics," *IEICE Trans.Elecron.*,vol.E90-C, No.12, pp 2185-2191, Dec., 2007.

[12] Reungyot Lerdwanittip, Apirada Namsang, Prayoot Akkaraekthalin, "A banspass filter using asymmetrical stepped impedance resonators and hook feed lines for harmonic suppression," *ITC-CSCC2010.*, pp.1160-1163, July, 2010.

[13] Zeland Software, Inc, *IE3D*, NewYork**.**

[14] J. S. Hong and M. J. Lancaster, "Theory and Experiment of Novel Microstrip Slow-Wave Open-Loop Resonator Filters," *IEEE Trans. Microwave Theory Tech*, Vol.45, No.12, pp.2358-2356, Dec., 1997.

Reungyot Lerdwanittip received the B.Eng. degree in Electronics Engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand in 2006. He is currently working toward for M.Eng. degree at King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand. His research interests include the design of microwave filters and associated RF modules for microwave and millimeter-wave applications.

Apirada Namsang received the B.Eng. degree in Electrical Engineering from Rajamangala University of Technology Thunyaburi (RMUTT), Klong 6, Thailand, in 1997, and the M.Eng. degree in Electrical Engineering from King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand in 2002. She is currently working toward for Ph.D. degree at KMUTNB. Her research interest is in the area of high frequency and microwave circuit design.

Prayoot Akkaraekthalin was born in Nakorn Pathom, Thailand. He received the B.Eng. and M.Eng. degrees in Electrical Engineering from King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand, in 1986 and 1990, respectively, and the Ph.D. degree from the University of Delaware, Newark, USA, in 1998. From 1986 to 1988, he worked in the Microtek Laboratory, Thailand, as a microwave research and development engineer. In 1988, he joined the Department of Electrical Engineering KMUTNB, as an instructor. His current research interests include passive and active microwave circuits, wideband and multiband antennas, and telecommunication systems. Dr.Prayoot is members of IEEE, IEICE Japan, and ECTI Thailand. He was the Chairman for the IEEE MTT/AP/ED Thailand Joint Chapter during 2007 and 2008. He currently serves as the Vice Chairman for the ECTI Association, Thailand.