Quarter-Wavelength Stub Bandpass Filter with T-type Inverter for Harmonic Suppressed Application

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Abstract

In this paper, the design method of stub bandpass filter (BPF) is suggested by equations of the tapped-line geometry and the $\lambda_g/4$ stub BPF with T-type inverter is implemented for the harmonic suppressing for ISM band. Design parameters for the tapped-line geometry are obtained using the equivalent circuit of the J-inverter for the filter prototypes and the T-type inverter is realized by the equivalent circuit of the quarter wavelength transmission-line. The harmonic suppressed $\lambda_g/4$ stub BPF is fabricated on Teflon substrate and its harmonics of the $\lambda_g/4$ stub BPF are suppressed over 30 dB up to 10 GHz.

Keywords: *bandpass filter (BPF), short-stub, harmonic, tapped-line, inverter*

1. Introduction

In the micrstrip filter, a tapped feeding method has been applied to various filter types such as a combline filter, an interdigital filter, an edge coupled filter, a square ring filter, and so on [1-8]. For the design of a filter using tapped-line, an open-wire-line equivalent circuit approach has been suggested [2, 3], and then the design method with the coupling coefficient, k, and the external quality factor, Q_e has been generally used when needed for complicated electro-magnetic (EM) field analysis [4-9].

The tapped feeding method is realized such that the J-inverter of filters is replaced with tapped feed-line. Especially, in our previous work, tapped-line is realized on the open-stub and additional transmission-line which has negative electrical length [7-9].

Otherwise, the stub bandpass filter (BPF) has been widely used because of its simplicity in implementation and easy connectivity with other components, although the stub BPF has a relatively broad bandwidth [5].

Also, in order to obtain high selectivity of BPFs, more resonators are used or the elliptic-function response is used such as open-loop resonators and ring resonators. The elliptic-function BPFs have transmission zeros and show high selectivity by using smaller number of the resonator [5]. As using tapped-line geometry, the transmission zero can be obtained by the open-stub and BPFs can be realized with high selectivity.

In this paper, a harmonics suppressed $\lambda_g/4$ short-stub BPF is suggested and realized by inserting the T-type equivalent circuit for the $\lambda_g/4$ transmission-line as the inverter. This filter provides compact design, sharp skirt characteristic, and second and third harmonics suppressed characteristic.

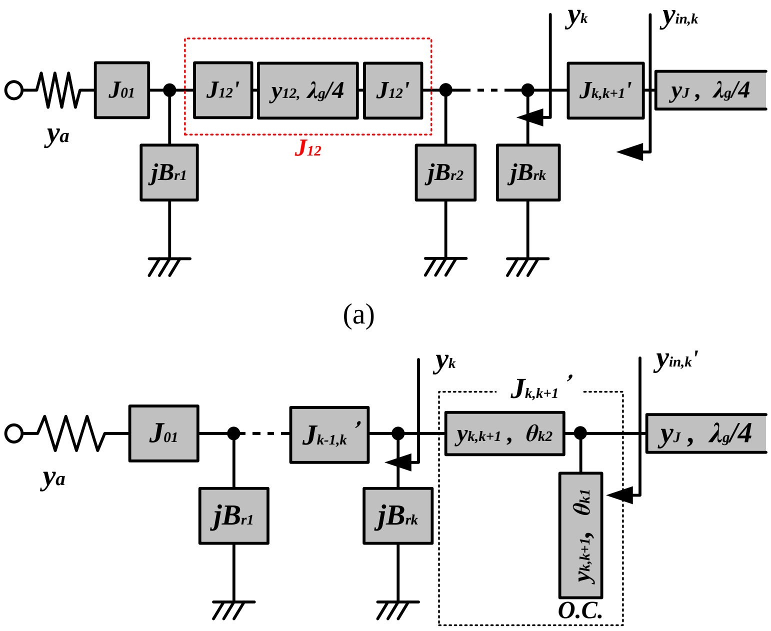
2. Analysis of Tapped-line Method for $\lambda_g/4$ Stub BPF

In our previous work, the *J*-inverter can be alternated as the open-stub and additional transmission-line, and their electrical lengths are as followed [7]:

$$\theta_{01} = \tan^{-1}\left\{ \frac{y_a^{\,2} - J_{01}^{\,2}}{J_{01}} \sqrt{\frac{y^2 - J_{01}^{\,2}}{y_a^{\,2} - J_{01}^{\,2}}} \right\}, \tag{1}$$

$$\theta_{02} = -\tan^{-1}\left\{ \frac{y}{J_{01}} \sqrt{\frac{y_a^{\,2} - J_{01}^{\,2}}{y^2 - J_{01}^{\,2}}} \right\}. \tag{2}$$

where θ_{01} and θ_{02} are the electrical length of the open-stub and transmission-line, respectively, and y and y_a are the normalized admittance of the line and source, respectively.



(a)

(b)

Figure 1. Configuration of the filter with (a) divided J-inverter and inner tapped-line, (b) an equivalent circuit

For the tapped-line method in the stub BPF, each *J*-inverter of the inner section is divided into three sections as shown in Figure 1(a) and ABCD parameters are used for the cascaded network because the overall parameters are computed by simply multiplying the matrices of the individual network.

Here, y_J is the normalized admittance of the $\lambda_g/4$ line as shown in Figure 1(a).

Figure 1(a) shows the circuit configuration of a filter with divided *J*-inverters. In Figure 1(a), because B_{rk} is 0 at the resonant frequency, the admittance toward source in the *k*'th resonator, y_k is given by

$$y_k = \begin{cases} \dfrac{1}{y_a} \cdot \dfrac{J_{01}{}^2 \cdot J_{23}{}^2 \cdots\cdots J_{k-1,k}{}^2}{J_{12}{}^2 \cdot J_{34}{}^2 \cdots\cdots J_{k-2,k-1}{}^2} & k\,;odd \\ y_a \cdot \dfrac{J_{12}{}^2 \cdot J_{34}{}^2 \cdots\cdots J_{k-1,k}{}^2}{J_{01}{}^2 \cdot J_{23}{}^2 \cdots\cdots J_{k-2,k-1}{}^2} & k\,;even \end{cases} . \tag{3}$$

The divided *J*-inverter can be represented by the equivalent circuit of the tapped-line as shown in Figure 1(b). The inner tapped-line is composed of the transmission-line and the open-stub with the normalized admittance, $y_{k,k+1}$. The electrical lengths of the stub (θ_{k1}) and line (θ_{k2}) for the inner tapped-line can be determined by the input admittance such as the case in tapped-line feeding. The input admittance toward source, $y_{in,k}'$ as shown in figure 1(b) can be obtained as

$$y_{in,k}' = y_{k,k+1} \cdot \frac{y_k + jy_{k,k+1} \tan\theta_{k2}}{y_{k,k+1} + jy_k \tan\theta_{k2}} + jy_{k,k+1} \tan\theta_{k1} . \tag{4}$$

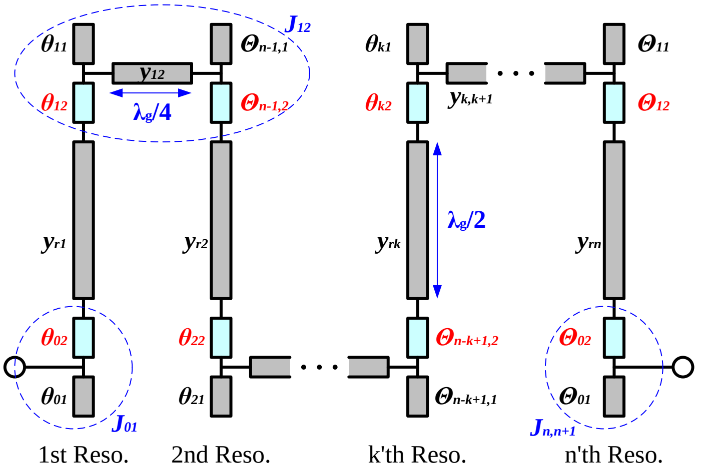
On the other hand, the normalized input admittance prior to the *k*'th inverter is given by

$$y_{in,k} = \frac{(J_{k,k+1}')^2}{y_k} . \tag{5}$$

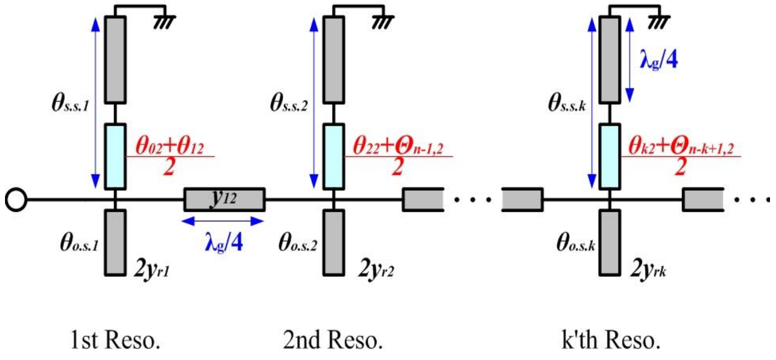
If the electrical length of the transmission-line is assumed to be negative such as the case in tapped-line feeding [8], the electrical lengths of the transmission-line θ_{k1} and the open-stub θ_{k2} in the *k*'th resonator can be given as equation (6) and (7), respectively, which are derived from equation (4) and (5).

$$\theta_{k1} = \tan^{-1} \frac{\sqrt{\left\{(J_{k,k+1}')^2 - y_k{}^2\right\}\left\{y_{k,k+1}{}^2 - (J_{k,k+1}')^2\right\}}}{y_{k,k+1}\, y_k} . \tag{6}$$

$$\theta_{k2} = -\tan^{-1}\left\{ \frac{y_{k,k+1}}{y_k} \sqrt{\frac{(J_{k,k+1}')^2 - y_k{}^2}{y_{k,k+1}{}^2 - (J_{k,k+1}')^2}} \right\} . \tag{7}$$



(a)



(b)

Figure 2. Schematic of (a) the $\lambda_g/2$ stub BPF and (b) $\lambda_g/4$ stub BPF using tapped-line geometry

A $\lambda_g/4$ stub BPF is suggested using tapped-line geometry as shown in Figure 2(a). In Figure 2, the resonators are connected by the $\lambda_g/4$ transmission-line. Also, $y_{k,k+1}$ is the admittance of the $\lambda_g/4$ line between resonators and θ_{01}, θ_{11}, and θ_{k1} are the electrical lengths of the open-stubs which are determined by equation (1) and (6) and θ_{02}, θ_{12}, and θ_{k2} are the electrical lengths of the transmission-lines with negative values which are determined by equation (2) and (7). Also, Θ_{01}, Θ_{11}, and $\Theta_{n-k+1,1}$ are the electrical lengths of the open-stubs and Θ_{02}, Θ_{12}, and $\Theta_{n-k+1,2}$ are the electrical lengths of the transmission-lines which are determined by the J-inverter and the output admittance toward load. The parameters for toward load can be obtained by substituting admittance toward load, y_{n-k} for one toward source, y_k. The normalized admittance toward load in the k'th resonator, y_{n-k} is defined as

$$y_{n-k} = \begin{cases} y_b \cdot \dfrac{J_{n-1,n}{}^2 \cdot J_{n-3,n-2}{}^2 \cdots\cdots J_{n-k,n-k+1}{}^2}{J_{n,n+1}{}^2 \cdot J_{n-2,n-1}{}^2 \cdots\cdots J_{n-k-1,n-k}{}^2} & (k < n) \\ & k\,;odd \\ \dfrac{1}{y_b} \cdot \dfrac{J_{n,n+1}{}^2 \cdot J_{n-2,n-1}{}^2 \cdots\cdots J_{n-k,n-k+1}{}^2}{J_{n-1,n}{}^2 \cdot J_{n-3,n-2}{}^2 \cdots\cdots J_{n-k-1,n-k}{}^2} & (k < n) \\ & k\,;even \end{cases} \tag{8}$$

where y_b is the normalized load admittance. In case of a symmetric structure such that a filter has an odd order and the same input and output admittance, Θ_k has the same value with θ_{n-k+1}.

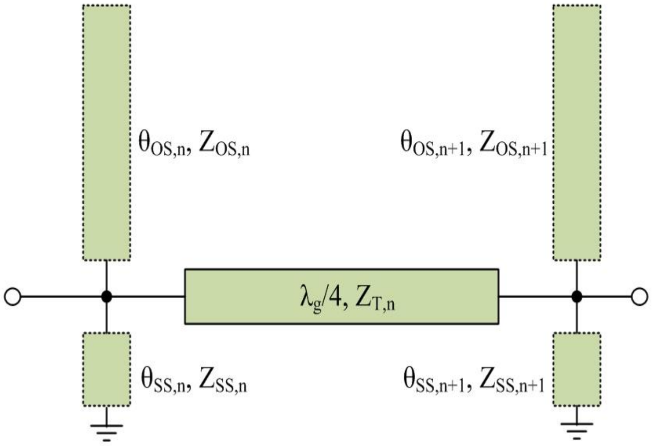
The $\lambda_g/4$ stub BPF can be designed as shown in Figure 2(b), where y_{rk} is the admittance of the k'th resonator. Because the admittance of each $\lambda_g/4$ resonator becomes twice as large as that of a $\lambda_g/2$ resonator, the $\lambda_g/4$ stub BPF can be designed using a $\lambda_g/4$ resonator with a double resonator admittance or with a half fractional bandwidth of a desired one. The electrical lengths of an open-stub and short-stub can be defined as follows [8]:

$$\theta_{o.s.1} = \frac{\theta_{01}+\theta_{11}}{2}, \quad \theta_{o.s.n} = \frac{\Theta_{11}+\Theta_{01}}{2}, \\ \theta_{o.s.k} = \frac{\theta_{k1}+\Theta_{n-k+1,1}}{2} \quad (k \le n-1) \tag{9}$$

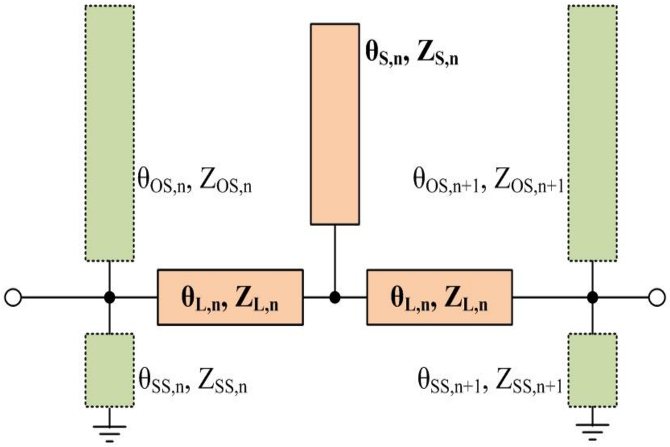
$$\theta_{s.s.1} = \frac{\lambda_g}{4} + \frac{\theta_{02}+\theta_{12}}{2}, \quad \theta_{s.s.n} = \frac{\lambda_g}{4} + \frac{\Theta_{12}+\Theta_{02}}{2}, \qquad (10)$$
$$\theta_{s.s.k} = \frac{\lambda_g}{4} + \frac{\theta_{k2}+\Theta_{n-k+1,2}}{2} \quad (k \le n-1)$$

and the electrical length of each resonator is almost quarter wavelength.

3. Design of Harmonic Suppressed $\lambda_g/4$ Stub BPF



(a)



(b)

Figure 3. Schematic of (a) the $\lambda_g/4$ line as the *n*'th inverter and (b) the T-type inverter as alternating by the T-type equivalent circuit for the $\lambda_g/4$ line

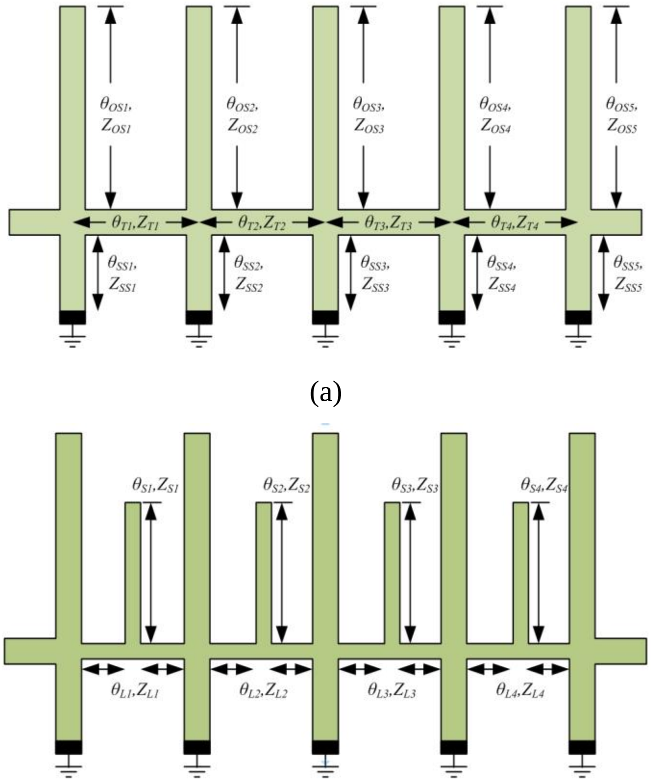
For the tapped-line geometry, the *J*-inverter can be alternated as the open-stub, short-stub, and additional transmission-line. Also, their electrical lengths and impedances are demonstrated. Figure 3(a) and (b) are the $\lambda_g/4$ line as the *n*'th inverter for the $\lambda_g/4$ stub filter and the T-type inverter as alternating by the T-type equivalent circuit for the $\lambda_g/4$ line, respectively, where Z_{in} is the characteristic impedance and θ_{in} is the electrical length of the stub and line (i = T, L, S, and n = 1, 2, 3). The T-type equivalent circuit of the $\lambda_g/4$ line can be obtained by using the ABCD matrix. General equations for Z_{Ln} and Z_{Sn} are derived as follows:

$$Z_{Ln} = \frac{Z_{Tn}}{\tan\theta_{Ln}}, \tag{11}$$

$$Z_{Sn} = \frac{Z_{Tn}\cdot\tan\theta_{Sn}}{1-\tan^2\theta_{Ln}}. \tag{12}$$

where Z_{Tn} is the impedance of the $\lambda_g/4$ line as the n'th inverter and Z_{Ln}, Z_{Sn}, θ_{Ln}, and θ_{Sn} are impedances and electrical lengths of the n'th line and stub, respectively.

Also, the $\lambda_g/4$ short-stub BPF using the tapped-line geometry can be designed as shown in Figure 4(a). The impedance and electrical lengths for the line and open/short-stub can be calculated from equation (9) and (10). Especially, the electrical length of the transmission-line as the k'th inverter, θ_{Tk} is 90°. For comparison, the stub and transmission-line as the inverter for the $\lambda_g/4$ stub BPF is designed 50 Ω, *i.e.*, $Z_{OSk} = Z_{SSk} = Z_{Tk} = 50\ \Omega$. To demonstrate the feasibility and usefulness of the design, the short-stub BPF using the tapped-line geometry is designed the 5th order chebyschev prototype filter with 0.01dB ripple and 10% bandwidth at the center frequency of 2.4 GHz.



(a)

(b)

Figure 4. Structure of (a) the $\lambda_g/4$ stub BPF with 5^{th} order and (b) the proposed harmonic suppressed stub BPF with the T-type inverter

Table 1. Parameters of the proposed harmonic suppressed $\lambda_g/4$ stub BPF

$\lambda_g/4$ short-stub BPF with T-type inverter			
$\theta_{OS1} = \theta_{OS5}$	75.45°	$\theta_{S1} = \theta_{S4}$	52.26°
$\theta_{SS1} = \theta_{SS5}$	14.37°	$\theta_{L1} = \theta_{L4}$	32.20°
$\theta_{OS2} = \theta_{OS4}$	79.39°	$\theta_{S2} = \theta_{S3}$	31.68°
$\theta_{SS2} = \theta_{OS4}$	10.98°	$\theta_{L2} = \theta_{L3}$	38.46°
θ_{OS3}	80.15°	$Z_{S1} = Z_{S4}$	107.7Ω
θ_{SS3}	9.68°	$Z_{L1} = Z_{L4}$	87.0Ω
		$Z_{S2} = Z_{S3}$	61.3Ω
		$Z_{L2} = Z_{L4}$	71.0Ω

Figure 4(b) shows the structure of the suggested harmonic suppressed stub BPF. Each $\lambda_g/4$ transmission-line in figure 4(a) is alternated the T-type inverter. In order to suppress the second and third-mode harmonics, two different T-type inverters with different electrical lengths of the open-stub are designed as shown in Figure 4(b). Parameters in Figure 4(b) can be obtained by using equation (11) and (12). Then, the parameters of two types of stub BPFs are summarized in Table 1. In Table 1, θ_{OSk} and θ_{SSk} are the electrical lengths of the *k*'th open-stub and short-stub, respectively. Also, θ_{Sk} and θ_{Lk} is the electrical lengths of the *k*'th stub and line, respectively, for the T-type inverter. As BPFs with odd order are symmetric, parameters of the BPF with 5th order are symmetric. Also, Z_{Sk} and Z_{Lk} are the impedance of the *k*'th stub and line, respectively.

4. Manufacturing and Results of Harmonic Suppressed Short-Stub Bandpass Filter

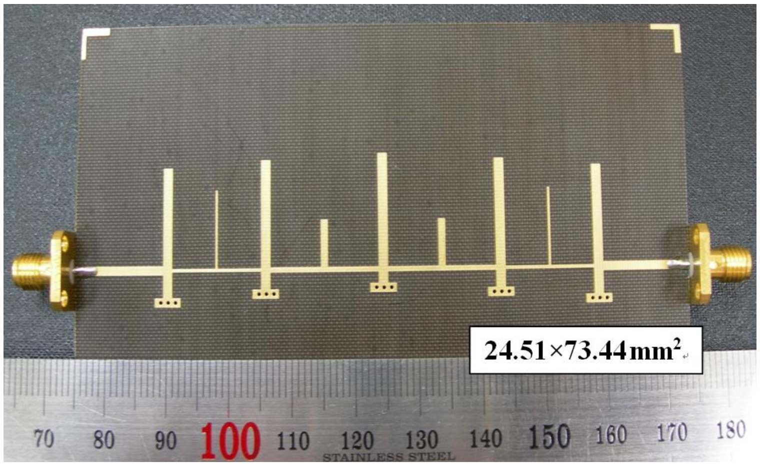


Figure 5. Fabricated harmonic suppressed $\lambda_g/4$ stub BPF with T-type inverter

In this paper, the harmonic suppressed stub BPF with the T-type inverter is design with the bandwidth of 10% at the center frequency of 2.4 GHz for ISM band using EM simulator. To validate the design concept, two filters are built on a copper coated tefron substrate with a dielectric constant of 2.54, a height of 0.54 mm, and a metal's thickness of 0.017 mm. In the experiment, the measurement has been done with an Agilent 8510C network analyzer using standard SMA connector. Figure 5 shows the photograph for the proposed harmonic suppressed stub BPF. The size of the proposed stub BPF is 24.51×73.44 mm^2.

The overall simulated and measurement results of the harmonic suppressed $\lambda_g/4$ stub BPF with inserted T-type inverter agree very well as shown in Figure 6. From the simulation results of the Figure 6, the conventional $\lambda_g/4$ stub BPF has the higher mode harmonics, however, the proposed stub BPF with T-type inverter has the characteristic of the second and third mode harmonics suppression up to 10 GHz. Also, the proposed short-stub BPF with T-type inverter is simulated with an insertion loss of 1.21 dB and a return loss of less than 20 dB at the center frequency 2.38 GHz. While the measurement data show the insertion loss of 1.64 dB and return loss of 20 dB at the center frequency of 2.37 GHz with suppressed harmonics under 30 dB up to 10 GHz by the additional open stubs of the T-type inverter.

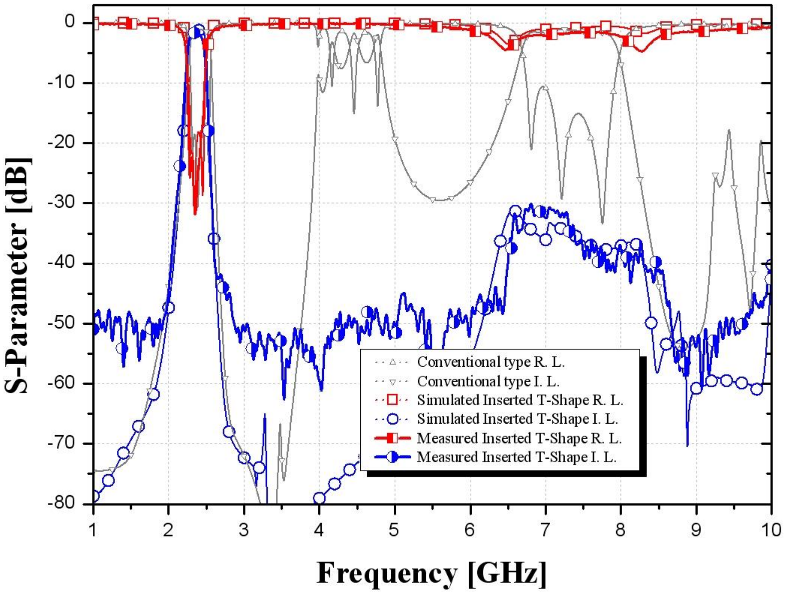


Figure 6. Simulated and measured results of frequency responses for the harmonic suppressed $\lambda_g/4$ stub BPF with T-type inverter

5. Conclusion

In this paper, a simplified design method of the harmonic suppressed short-stub BPF for ISM applications is proposed by using the conventional short-stub BPF with inserted T-type inverter. The T-type inverter can be designed by the equivalent circuit of the quarter wavelength transmission-line and can be suppressed harmonics by the open-stub. Proposed short-stub BPF has two different T-type inverters and the second and third-mode harmonics of the proposed short-stub BPF are rejected.

Also, the suggested short-stub BPF design allows narrower bandwidth and suppressed the second and third mode harmonics implementation compared to the conventional short-stub BPF which is typically provided. The proposed filter is easily implemented and integrated with other devices and circuits.

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