IMPROVING FREQUENCY RESPONSE OF MICROSTRIP FILTERS USING DEFECTED GROUND AND DEFECTED MICROSTRIP STRUCTURES

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Abstract—In this work, the introduction of Defected Microstrip Structures and Defected Ground Structures is presented to improve the performance of a traditional stepped-impedance microstrip lowpass filter. The attenuation in the stop-band is enhanced by more than 15 dB and selectivity is increased, without modifying the insertion loss in the pass band. A comparison of characteristics in filters is made when the combination of Defected Ground and Defected Microstrip Structures, as well as when only the first one are used. A model of the Defected Microstrip Structure and the corresponding equations to obtain the equivalent lumped and distributed element values are also given.

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1. INTRODUCTION

Filters play an important role in most RF and Microwave applications. Currently, the electromagnetic spectrum is limited, and the applications are restricted to occupy just a portion of frequency range without affecting the equipment working out of band and also, without being affected by adjacent devices.

Emerging applications such as wireless communications continue challenging RF/microwave filters performance with even more stringent requirements, higher performance, smaller size, lighter weights, and low cost. Depending on the requirements and specifications, filters can mainly be designed with lumped or distributed elements.

Microstrip structures have been an interesting alternative to perform as RF and microwave filters, with good trade-offs regarding selectivity, insertion loss, volume, size, among other requirements.

Recently, the proposal of a new kind of structure called Defected Ground Structure (DGS) [1] has given origin to different applications in passive circuits.

The stop-band inherent behavior of such structure gives the opportunity to apply this effect to better the characteristics of certain devices, like improving the efficiency of power amplifiers [2], enhancing the performance of patch antennas [3], reducing the size of microwave circuits, including amplifiers [4, 5], harmonic filtering [6], and so on.

Another important application concerning filtering is the use of Defected Ground Structure to improve the frequency response of low-pass filters, and many papers have been done regarding this application [7, 8].

On the other hand, a new interesting configuration called Defected Microstrip Structure has been successfully employed as a technique to reduce the size and tuning of rectangular patch antennas [9, 10, 18]. It shows a stop-band behavior similar to the Defected Ground Structure performance.

The use of distributed element circuits is well known to develop or substitute lumped elements in the design of filters. For example, the main advantage of stepped-impedance filters is the simplicity [11], but the low selectivity and low attenuation obtained in the stop-band are very important drawbacks. In order to diminish this limitation in [12] two Defected Ground unit-cells were employed, although the insertion loss in the stop-band was improved, it presented a low attenuation at a frequency band away from the cutoff frequency.

Here, it will be shown that by introducing the Defected Microstrip Structure and complementing with DGS cells in such filters, the

attenuation in the stop-band can be made deeper than 15 dB all over the required rejection band. This technique allows improving the selectivity without affecting the insertion loss in the band-pass.

2. DEFECTED MICROSTRIP AND DEFECTED GROUND STRUCTURES

Defected Microstrip and Defected Ground Structures applied in passive circuits introduce a slow-wave effect, and this phenomenon can be very useful for certain applications. The associated inductance of a Defected Ground unit-cell may represent a required inductor on a microstrip filter [11, 13].

On the other hand, the Defected Microstrip can be employed to add an extra attenuation in the stop-band, and to increase the selectivity of the filter as it will be proved in the next sections. The structures used to enhance the amplitude-frequency characteristic of a stepped-impedance low-pass filter are shown in Figure 1.

3. MODELS OF DEFECTED MICROSTRIP AND DEFECTED GROUND STRUCTURES

As it was pointed out before, Defected Microstrip and Defected Ground structures have a similar behavior. In the second structure, the imperfection is etched over the ground plane, whereas in the first one, the slot is introduced over the microstrip line, as it is displayed in Figure 1. The slow wave factor over the microstrip is increased since
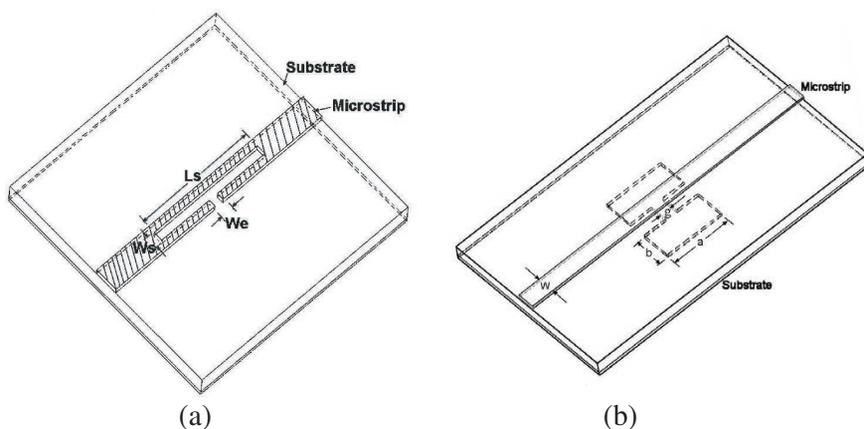

Figure 1. (a) Defected microstrip and, (b) defected ground structures.

the current distribution is perturbed due to the trajectory followed around the slot line as observed in Figure 2(a). A frequency response comparison for both structures is depicted in Figure 2(b).

Figure 2 presents the frequency performance of a Defected Ground unit-cell and a Defected Microstrip unit-cell over a substrate with permittivity of 10, and thickness of 0.625 mm. From these curves, it can be assured that they behave like an L-C resonant circuit, but showing a bigger quality factor in the case of the slotted line. This fact means that both structures can suitably be modeled by an L-C circuit. From [12], the parameters of the Defected Ground are acquired by using the equations obtained from the model given in Figure 3.

$$X_{LC} = \frac{1}{\omega_0 C\left((\omega_0/\omega) - (\omega/\omega_0)\right)} \quad (1)$$

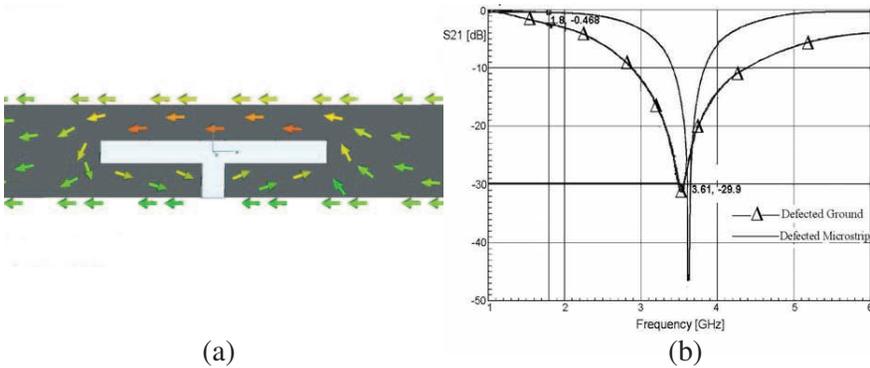(a)   (b)

Figure 2. (a) Current distribution over a microstrip line with DMS. (b) Frequency response of defected structures.

(a)   (b)
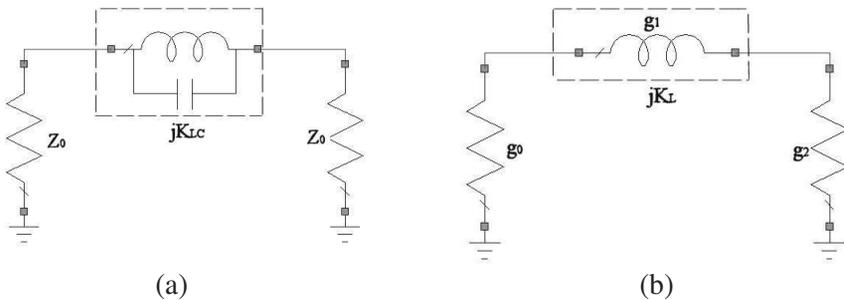
Figure 3. (a) Equivalent model for a unit-cell defected ground structure and, (b) one-pole butterworth prototype.

$$X_L = \omega' Z_0 g_1 \tag{2}$$

$$X_L \big|_{\omega=\omega_0} = X_L \big|_{\omega'=1} \tag{3}$$

where ω_0, ω', g_1 and Z_0 are the resonant frequency, normalized cutoff frequency, prototype value of the Butterworth-type low-pass filter, and the scaled port impedance, respectively. The extraction of the resonant frequency, cutoff frequency and attenuation pole is obtained from electromagnetic simulation (EM). This model is also used in [13, 14].

As well as Defected Ground, Defected Microstrip can be represented by lumped and distributed parameter elements. After some studies [9, 10, 15], fitting the model proposed in [16], it was found that this structure is well described by a series inductor performing the associated inductance. The inductor is connected in parallel to a short circuited transmission line with impedance Z_S and electric length θ, which represents the periodic behavior of the line. Figure 4(a) depicts the model in lumped and distributed elements, and 4(b) the Butterworth-type low-pass filter.

As in the case of Defected Ground, the Defected Microstrip model is compared to the performance of a one-pole Butterworth-type, since similar properties can be seen in both circuits. The corresponding equations are obtained.

According to Figure 4, for the DMS model, the equations are as follows:

$$X_S = j \frac{Z_S \omega L_S \tan \theta}{\omega L_S + Z_S \tan \theta} \tag{4}$$

$$X_B = j\omega L_B \tag{5}$$

where X_S, Z_S, θ, L_S are the reactance of the equivalent circuit, the transmission line impedance, the electric length of the line and the
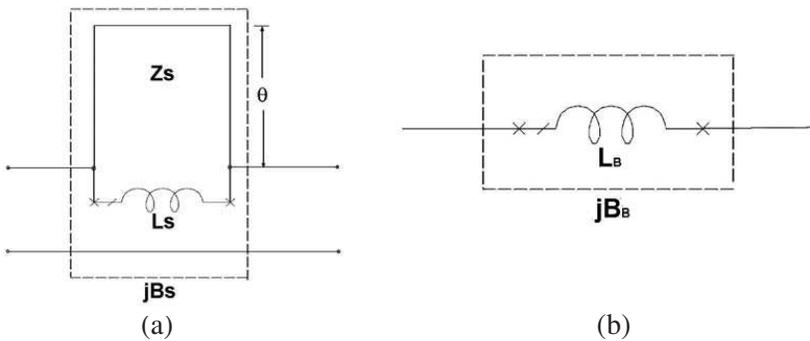

Figure 4. (a) Equivalent circuit model for defected microstrip structure and, (b) one-pole Butterworth-type.

associated inductance of the model, respectively. X_B is the reactance of the one-pole Butterworth-type low-pass filter.

To find the values of the elements in the model, (4) and (5) are solved simultaneously, considering the conditions of resonance of both circuits, where the susceptance and reactance should be equal to zero. At the cutoff frequency, (4) is equal to (5). At the frequency where the pole is located, the condition that satisfies the equations is $\theta = 0°$ or $180°$. Then, such conditions give the following pair of equations:

$$L_S = \frac{L_B \left(f_0 \cot\theta_0 - f_C \cot\theta_C\right)}{f_0 \cot\theta_0} \tag{6}$$

$$Y_S = -\frac{1}{2\pi f_0 L_S \cot\theta_0} \tag{7}$$

where θ_0 and θ_C are the electric length of the line at the resonant frequency, f_0, and the $-3\,\text{dB}$ cutoff frequency, f_C, respectively. The required frequencies for the solution of equations are obtained extracting the parameters from an EM simulation.

4. STEPPED-IMPEDANCE LOW-PASS FILTER

Figure 5 shows a general structure of the stepped-impedance low-pass filter, which uses a cascade structure, alternating high- and low-impedance transmission lines.

The high-impedance lines act as series inductors and the low-impedance lines perform as shunt capacitors. Therefore, this filter structure is, directly, realizing the L-C ladder type of a low-pass filter.

In order to explain the designing method and compare results to previous published work [12], a three pole $1\,\text{GHz}$ cutoff frequency low-pass filter is designed considering a Butterworth response, whose element values are:

$$g_0 = g_4 = 1$$
$$g_1 = g_3 = 1$$
$$g_2 = 2$$

Using the respective transformation, the element values are:

$$L_1 = L_3 = 7.957\,\text{nH} \quad \text{and} \quad C_2 = 6.366\,\text{pF}.$$

Figure 5. General structure of a stepped-impedance low-pass filter.

The design of such filters can be made for higher frequencies where lumped elements do not perform adequately. The implementation of the prototype as a microstrip filter is simulated on a substrate with dielectric constant of 10.8 and thickness of 1.27 mm. For emulation of the inductors, a characteristic impedance $Z_{0L} = 95\,\Omega$ is chosen, and the impedance line for the capacitor is $Z_{0C} = 25\,\Omega$.

To find the required dimensions of the filter, the following equations must be solved for l_C and l_L [11], which are the physical lengths of the lines for the capacitor and inductor, respectively.

$$2\pi f_C L = Z_{0L} \sin\left(\frac{2\pi l_L}{\lambda_{gL}}\right) + Z_{0C} \tan\left(\frac{\pi l_C}{\lambda_{gC}}\right) \tag{8}$$

$$2\pi f_C C = \frac{1}{Z_{0C}} \sin\left(\frac{2\pi l_C}{\lambda_{gC}}\right) + \frac{2}{Z_{0L}} \tan\left(\frac{\pi l_L}{\lambda_{gL}}\right) \tag{9}$$

where L is the inductance, C is the capacitance, λ_{gC} and λ_{gL} are the wavelengths on the low- and high-impedance lines, respectively. According to microstrip line design, the values obtained are given in Table 1.

Solving (8) and (9), takes to $l_C = 7.11\,\text{mm}$, and $l_L = 9.8\,\text{mm}$. Results obtained by simulation are shown in Figure 6. In this figure, it is clearly observed a low-pass response with cutoff frequency a little higher than 1 GHz, this phenomenon is obtained because the uncompleted compensation of parasitic series reactance and shunt susceptance of low- and high-impedance lines, respectively as it is shown in [11]. Besides, it is also seen that the insertion loss in the band of rejection is very poor (about 10 dB). Moreover, at higher frequencies, the band of rejection shows a very light attenuation; therefore, strictly speaking, the circuit behaves as a stop- band filter, and the performance is not adequate when there is a necessity of filtering oscillations with components over a wide frequency range [12]. One solution to this problem is the use of open-circuited stubs, but this technique only improves the attenuation over a narrow range in the stop- band close to the cutoff frequency. However, at higher frequencies the phenomenon is kept, this means, the loss is very low at those frequencies, as it is pointed out in Figure 6.

Table 1. Characteristics of microstrip lines for the 1 GHz low-pass filter.

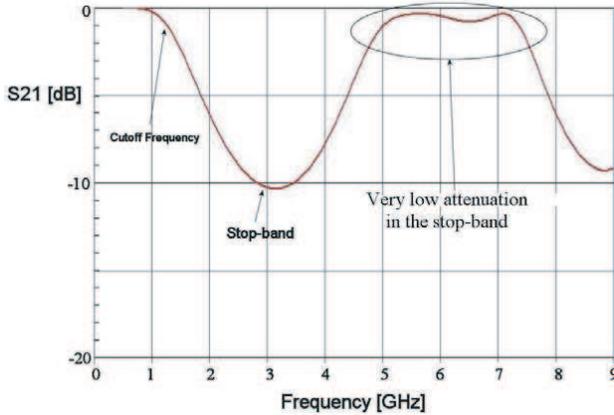| $Z_{0C} = 25\,\Omega$	$W_C = 4.0\,\text{mm}$	$\lambda_{gC} = 105\,\text{mm}$
$Z_{0L} = 95\,\Omega$	$W_L = 0.20\,\text{mm}$	$\lambda_{gL} = 118\,\text{mm}$
$Z_0 = 50\,\Omega$	$W_0 = 1.1\,\text{mm}$	$\lambda_{g0} = 112\,\text{mm}$

Figure 6. Frequency response of the 1 GHz microstrip low-pass filter.

An improvement of this type of filters is proposed in [12]. In that work, Defected Ground unit-cells are employed with the goal of substituting the use of high-impedance lines, representing the required inductors, and use the associated inductance of the structure to obtain the value of the inductor.

A three-pole low-pass filter was designed, using two Defected Ground cells and a low-impedance line for the prototype. However, even the good convergence of results obtained from the harmonic balance simulator, electromagnetic simulator and measurements, this type of filter shows a similar disadvantage to the stepped-impedance filter, concerning low attenuation at higher frequencies in the stop-band range.

In order to prove this fact, the specifications given in [12] were considered for a new simulation in HFSS over a wider frequency rage, and results, obtained from this process, are depicted in Figure 7, in which, it is observed a curve with markers showing low attenuation when the response moves away from the cutoff frequency.

This performance is common in microstrip filters, since transmission lines have a periodic behavior over a wide frequency range [17]. To corroborate this fact and following the procedure proposed in [12], another low-pass filter was designed and simulated. The cutoff frequency is 1 GHz, and designed with two Defected Ground cells for replacing the high-impedance lines. The prototype is built in a substrate with permittivity of 10.8 and 0.625 mm of thickness. For these cells, dimensions are 8 mm by 12 mm. Characteristics of the microstrip filter are given in Section 6.
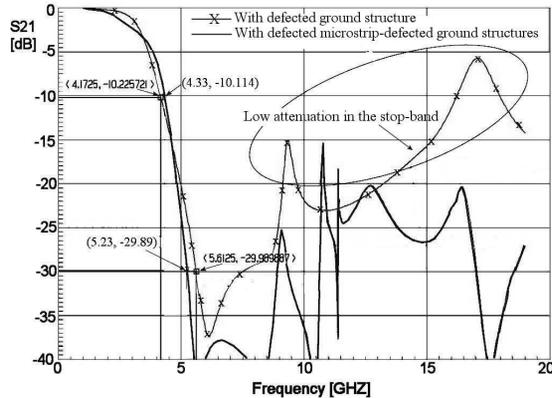
Figure 7. Frequency response of low-pass filter with defected ground structure [12] over a wider frequency range, and with defected microstrip-defected ground structures.

5. USE OF DEFECTED MICROSTRIP STRUCTURE IN MICROSTRIP LOW-PASS FILTER

In previous sections, it was observed that the implementations of low-pass filter with microstrip lines and a combination of stepped-impedance and Defected Ground cells show a frequency response which is not completely adequate at frequencies away from the cutoff frequency, even when the use of Defected Ground Structures enhance the performance of such filters.

In this work, it will be proved that the use of Defected Microstrip Structures is very useful for improving the stop-band attenuation of microstrip filters. This means, the simultaneous employment of DMS and DGS is an efficient tool to develop microstrip filters with a deep attenuation in the stop-band without degrading the selectivity or increasing the insertion loss in the pass-band.

Back to the design of [12], and observing the curve with markers in Figure 7, two Defected Microstrip Structures were added to the filter. One Defected Line was designed to resonate at 18 GHz, and the second unit-cell at 10 GHz. The filter structure is displayed in Figure 8.

The first Defected Microstrip has dimensions of 8 mm long by 0.25 mm wide, and the second cell is 4 mm long by 0.25 mm wide. Equivalent circuit model of the structure can be obtained by extracting the parameters from EM simulation, and solving Equations (6) and (7).

The frequency response with the proposed modification of the filter obtained by EM simulation is also depicted in Figure 7 to be
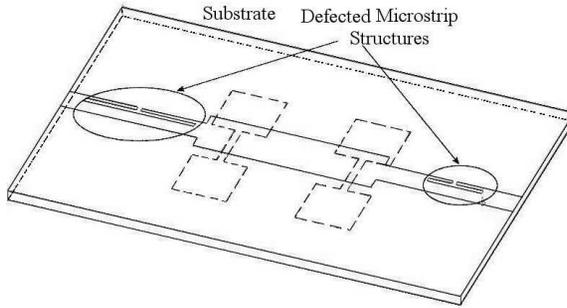
Figure 8. Microstrip low-pass filter with defected microstrip-defected ground structures.

compared to the DGS filter. From this figure, it is observed how the response in the stop-band is improved, obtaining attenuations less than 20 dB, almost all over the band of rejection, in comparison with the response obtained when just Defected Ground cells are employed. Moreover, the use of Defected Microstrip Structures in the prototype, gives another important advantage: the selectivity is improved. Comparing curves in Figure 7, an enhancement of this parameter is obtained, since the slope of the filter with DMS-DGS combinations is bigger. Filter with just Defected Ground unit cells shows an attenuation factor of $20\,\text{dB}/1.44\,\text{GHz} = 13.88\,\text{dB/GHz}$, and filter with the combination of the two structures presents an attenuation factor of $20\,\text{dB}/0.9\,\text{GHz} = 22.2\,\text{dB/GHz}$.

Then, it can be assured that by using Defected Microstrip Structures in a Defected Ground/stepped-impedance low-pass filter, the frequency response is highly improved, including an enhancement of selectivity.

6. RESULTS

Considering the specifications in Section 4, for the 1 GHz cutoff frequency low-pass filter, a prototype without Defected Microstrip and Defected Ground cells is designed and built on Duroid 6010 with dielectric constant of 10.8 and thickness of 0.625 mm. Solving Equations (8) and (9), for $Z_{OL} = 25\,\Omega$, $Z_0 = 95\,\Omega$ and $Z_0 = 50\,\Omega$, we have $l_C = 7.94\,\text{mm}$, $l_L = 12.85\,\text{mm}$, for $W_C = 2.82\,\text{mm}$, and $W_L = 0.25\,\text{mm}$.

This filter was simulated and measured, and results are displayed in Figure 9. The disadvantage pointed out before is observed, where

the periodic behavior of the transmission line carries out the poor attenuation over the stop-band at higher frequencies.

By using the method in [12] the high-impedance microstrip lines are substituted by Defected Ground cells. The size obtained for the Ground plane cells is 12 mm by 8 mm. The results by simulation for this filter are shown in Figure 10. In this figure, a similar behavior to the filter studied before is obtained.

After analyzing the dotted curve on Figure 10, it was decided to use two Defected Microstrip cells. The first structure has dimensions of 10 mm long by 0.25 mm wide, and the second cell is 14 mm long by 0.25 mm wide, resonating at 7.0 GHz and 4.5 GHz, respectively.

Simulated and measured results of the Stepped-impedance low-pass filter with Defected Microstrip-Defected Ground structure are also given in Figure 10, in which a great enhancement of frequency response of the filter is observed, concerning attenuation in the stop-band. From Figures 9 and 10, a comparison of performance between conventional stepped-impedance low-pass filter and frequency response of the filter by adding DMS cells is displayed, including the improvement of selectivity.

The insertion loss in the pass-band is close to 0.2 dB. The total dimensions of the stepped-impedance filter with imperfect structures are comparable to the size of the conventional stepped-impedance filter. Photograph of the prototype is shown in Figure 11.
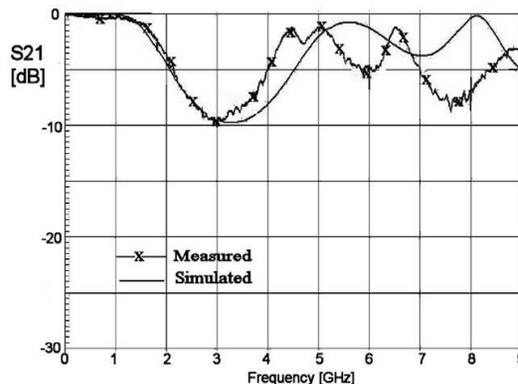

Figure 9. Simulated and measured frequency response of 1 GHz cutoff low-pass filter.
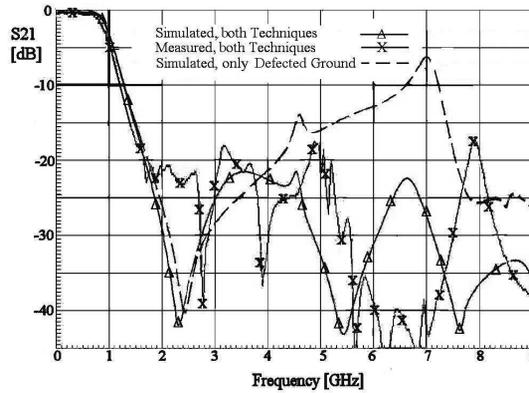
Figure 10. Comparison of frequency response of low-pass filter with only defected ground structure and the combination of defected microstrip and defected ground structures.
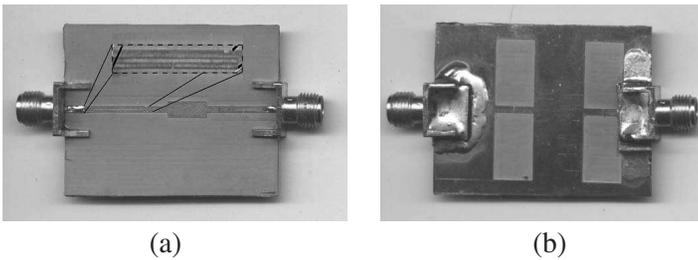

(a)   (b)

Figure 11. Microstrip low-pass filter with defected microstrip-defected ground structures. (a) Front view, (b) back view.

7. CONCLUSION

In the present work, the introduction of Defected Microstrip Structures is proposed to enhance the behavior of a microstrip stepped-impedance low-pass filter. Following the procedure in [12], the Defected Ground unit-cells are used to substitute the high-impedance lines because of the associated inductance of these structures, which are selected to perform like the inductors needed in the filter. However, the disadvantage of having a low attenuation at higher frequencies over the stop-band, which is a characteristic of most microstrip filters, is also observed in the combination microstrip line-Defected Ground prototype. This drawback is overcome by using Defected Microstrip cells, which are designed to resonate at certain frequencies where the attenuation is low. The model for Defected Microstrip

Structure is also explained and elements are obtained by extracting the required frequencies and parameters by using EM simulation, following a similar procedure reported for different models of Defected Ground Structures. The design method is also valid for higher frequencies where lumped elements are not recommended to be employed. The simultaneous use of these two techniques can be an efficient alternative to design microstrip filters, enhancing amplitude-frequency characteristics, extrapolating the applications to other kinds of responses like band-stop, band-pass or high-pass filters.

REFERENCES

1. Kim, C.-S., J.-S. Park, D. Ahn, and J.-B. Lim, "A novel 1-D periodic defected ground structure for planar circuits," *IEEE Microwave and Guided Wave Letters*, Vol. 10, No. 4, 131–133, Apr. 2000.

2. Lim, J.-S., H.-S. Kim, J.-S. Park, D. Ahn, and S. Nam, "A power amplifier with efficiency improved using defected ground structure," *IEEE Microwave and Wireless Components Letters*, Vol. 11, No. 4, 170–172, Apr. 2001.

3. Andrenko, A. S., Y. Ikeda, and O. Ishida, "Application of PBG microstrip circuits for enhancing the performance of high-density substrate patch antenna," *Microwave and Optical Technology Letters*, Vol. 32, No. 5, 340–344, Mar. 5, 2002.

4. Lim, J.-S., Y.-T. Lee, C.-S. Kim, D. Ahn, and S. Nam, "A vertically periodic defected ground structure and its application in reducing the size of microwave circuits," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 12, 479–481, Dec. 2002.

5. Lim, J.-S., J.-S. Park, Y.-T. Lee, D. Ahn, and S. Nam, "Application of defected ground structure in reducing the size of amplifiers," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 7, 261–263, Jul. 2002.

6. Jeong, Y.-C., S.-G. Jeong, J.-S. Lim, and S. Nam, "A new method to suppress harmonics using $\lambda/4$ bias line combined by defected ground structure in power amplifiers," *IEEE Microwave and Wireless Components Letters*, Vol. 13, No. 12, 538–540, Dec. 2003.

7. Karmakar, N. C. and M. N. Mollah, "Investigation into nonuniform photonic-bandgap microstripline low-pass filters," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 51, No. 2, 564–572, Feb. 2003.

8. Garde, L., M. J. Yabar, and C. Rios, "Simple modeling of

DGS to design 1D-PBG low-pass filters," *Microwave and Optical Technology Letters*, Vol. 37, No. 3, 228–232, May 5, 2003.

9. Tirado-Mendez, J. A., H. Jardon, et al., "A proposed defected microstrip structure (DMS) behavior for reducing rectangular patch antenna size," *Microwave and Optical Technology Letters*, Vol. 43, No. 6, 481–484, Dec. 20, 2004.

10. Tirado-Mendez, J. A., H. Jardon-Aguilar, and F. Iturbide-Sanchez, "Application of defected microstrip structure as a tuning technique for rectangular printed antennas," *Microwave and Optical Technology Letters*, Vol. 48, No. 2, 370–373, Feb. 2006.

11. Hong, J.-S. and M. J. Lancaster, *Microstrip Filters for RF/microwave Applications*, John Wiley & Sons, Inc., 2001.

12. Lim, J.-S., C.-S. Kim, Y.-T. Lee, D. Ahn, and S. Nam, "Design of lowpass filters using defected ground structure and compensated microstrip line," *Electron. Lett.*, Vol. 38, No. 22, 1357–1358, Oct. 24, 2002.

13. Lim, J.-S., C.-S. Kim, D. Ahn, Y.-C. Jeong, and S. Nam, "Design of low-pass filters using defected ground structure," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 53, No. 8, 2539–2545, Aug. 2005.

14. Ahn, D., J.-S. Park, C.-S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 49, No. 1, 86–93, Jan. 2001.

15. Tirado-Mendez, J. A., H. Jardon-Aguilar, E. A. Andrade-Gonzalez, and M. Reyes-Ayala, "Improving the performance of planar passive circuits by using defected microstrip structures," *WSEAS Transactions on Circuits and Systems*, No. 8, Vol. 5, 1356–1360, Aug. 2006.

16. Kim, C.-S., J.-S. Lim, S. Nam, K.-Y. Kang, and D. Ahn, "Equivalent circuit modeling of spiral defected ground structure for microstrip line," *Electron. Lett.*, Vol. 38, No. 19, 1109–1110, Sep. 12, 2002.

17. Pozar, D., *Microwave Engineering*, 3rd Edition, John Wiley & Sons, Inc., 1998.

18. Fallahzadeh, S. and M. Tayarani, "A compact microstrip bandstop filter," *Progress In Electromagnetics Research Letters*, Vol. 11, 167–172, 2009.