Research Article

Design of a Suspended Stripline Narrow Bandpass Filter with Ultrawideband Harmonic Suppression

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A design method of narrow bandpass filters (NBPFs) of 4–6% bandwidth with ultrawideband suppression of harmonic passbands, utilizing two cascaded step impedance resonators (SIRs) in a suspended stripline, is proposed in this paper. The proposed design utilized the characteristics of a suspended stripline, which provides a much higher characteristic impedance ratio as compared with that of the microstripline, enabling ultrawideband harmonic suppression. As an example of the NBPF, a filter with a passband center frequency f_0 of 0.75 GHz and bandwidth of 5% was implemented and proved to suppress the harmonic passbands up to $13.5f_0$. Since the proposed filter was implemented on the suspended stripline, the passband insertion loss was only -0.9 dB, which is low as compared with other previous designs. The proposed filter is a compact high-performance low-loss NBPF, which can be applicable to various wireless systems.

1. Introduction

Narrow bandpass filters (NBPFs) are often required for multimode and multiband operations in various wireless systems in order to remove multiple spurious frequency components existing very close to the desired passband frequency. Therefore, a variety of research have been performed worldwide to develop practical and high-performance NBPFs. For BPFs with 4–6% bandwidth, high-Q resonant structures such as open-loop resonators (OLRs) and step impedance resonators (SIRs) were used [1–5]. Typically, these resonant structures for NBPFs were conveniently formed in a microstripline (MSL).

In addition to a narrow passband around the center frequency, these NBPFs typically have a property of having undesired multiple harmonic passbands at odd-harmonic frequencies of the passband center frequency. For example, if the passband center frequency of the NBPF is a few GHz, there exist multiple harmonic passbands and problematic odd-harmonic passbands extending 10's of GHz within the system operation bandwidth. In order to suppress the multiple harmonic passbands, the receiver circuits sometimes become complicated by adopting ASIC (Application-Specific

Integrated Circuit) which uses high speed digital switching circuits or RF switches which use multifilter banks [6]. Therefore, the designs of the multiband system and duplexers become complicated.

Recently, significant research efforts have been performed in designing NBPFs with harmonic suppression for wideband frequencies. In [1], the filter was implemented using both sides of the substrate with multiple vias, but the fabrication was complicated and high insertion loss occurred. An open-ended filter structure, also used as a switch with diodes, was proposed in [2], but the proposed structure was complicated and the size was big. In [3], the size of the NBPF was reduced by adopting stubs, but the passband insertion loss was high, and the design process was complicated. In [4], a folded step impedance resonator (SIR) was used for the NBPF, but the insertion loss was high. In [5], a hairpin structure with a coupled line was used for the NBPF, and harmonic passband suppression up to $1.8f_0$ was obtained, but the suppression range was relatively small and the insertion loss due to slot line was significant.

An SIR is one of the utilized methods for the suppression of harmonics, and these SIR filters were mostly implemented in MSL-based circuits. The harmonic suppression bandwidth,

FIGURE 1: Configurations of (a) a hairpin step impedance resonator (SIR) consisting of three line segments with two characteristic impedances (Z_p and Z_s) and (b) the equivalent circuit of the hairpin SIR.

however, was somewhat limited since it is proportional to the maximum-to-minimum ratio characteristic impedance with practical microstripline (MSL) fabrications (15–120 Ω). On the other hand, the suspended stripline (SSL) can have a much wider range of the characteristic impedances (5–300 Ω) than that of the MSL. Therefore, a much wider harmonic suppression bandwidth can be accomplished with the SIR filter structure in SSL.

In this paper, a new design procedure for 4–6% NBPF filters in SSL using two cascaded SIR structures is proposed. By utilizing the ultrawideband MSL-to-SSL transition, which was developed by the authors' group [7] and can be easily integrated with the MSL-based circuits, this paper proposes a design method for a SSL NBPF with ultrawide harmonic suppression and low insertion loss. The center frequency of the proposed NBPF can be designed up to mm-wave frequency, but, in order to demonstrate the maximum harmonic suppression bandwidth, the filter center frequency of 0.75 GHz was chosen, resulting in an ultrawide harmonic suppression bandwidth of $13.5 f_0$.

2. Design of a Narrow Bandpass Filter in SSL

2.1. Calculation of Harmonic Suppression Bandwidth. Figure 1(a) illustrates a configuration of a step impedance resonator (SIR) consisting of three consecutive lines with two different characteristic impedances (Z_p and Z_s). Figure 1(b) shows an equivalent circuit of the hairpin-type SIR consisting of a parallel connection of two low-impedance lines (Z_p), which are folded and coupled, and one straight, high-impedance line (Z_s). Y_i and Y_o are the input and output admittance, respectively. Coupling of the low-impedance lines (Z_p) makes the impedance lower than that of a single uncoupled line. For the hairpin SIR structure, the calculation method of the characteristic impedance ratio K and the harmonic suppression bandwidth Δf_{SB} was given in [8]. The relationship between the two characteristic impedances and electrical line lengths of the SIR is given as

$$\tan \theta_s \cdot \tan \theta_p = \frac{Z_p}{Z_s} = K \quad (1)$$

where K is the ratio of characteristic impedances of Z_p and Z_s , and θ_p and θ_s are the electrical line lengths of the coupled line and straight single line, respectively.

To simplify the design process, we assume that $\theta_s = \theta_p = \theta_0$ where θ_0 is the electrical line length corresponding to the passband center frequency f_0 . Then, the suppression bandwidth of harmonic passbands of the hairpin SIR, Δf_{SB} , can be expressed as

$$\Delta f_{SB} = f_{SB} - f_0 = \left(\frac{\pi}{\tan^{-1} \sqrt{K}} - 1 \right) f_0 \quad (2)$$

where f_{SB} is the center frequency of the unsuppressed harmonic passband of the SIR. In (2), the harmonic suppression bandwidth Δf_{SB} increases if the impedance ratio K decreases or the magnitude difference between Z_p and Z_s increases. The characteristic impedances of the lines (Z_p and Z_s) of the SIR can be determined if the harmonic suppression bandwidth Δf_{SB} is chosen. If the SIR is implemented in MSL, the range of realizable characteristic impedances is 15–120 Ω , and the maximum Δf_{SB} can be calculated as $\Delta f_{SB} = 3.6 f_0$ using (2) with the minimum-to-maximum impedance ratio K . On the other hand, if the SIR circuit is made in SSL, the maximum Δf_{SB} can be as wide as $\Delta f_{SB} = 13.5 f_0$ since the range of realizable characteristic impedances is 5–300 Ω : that is, the maximum harmonic suppression bandwidth Δf_{SB} of the SIR implemented in SSL is about three times than that with MSL in Figure 2.

2.2. Design of the NBPF Using Two-Hairpin SIRs

2.2.1. Single-Hairpin SIR. With a hairpin SIR, the line length θ_0 changes according to the impedance ratio K . To design a NBPF with the hairpin SIRs, first, the characteristic impedance ratio K and the corresponding electrical lengths for Z_p and Z_s should be determined. As an example of the proposed hairpin SIR filter, the impedance ratio is chosen as $K = 0.015$ ($Z_p = 5 \Omega$, $Z_s = 300 \Omega$), then the harmonic suppression bandwidth is calculated as $\Delta f_{SB} =$

FIGURE 2: Variation of the normalized harmonic suppression $\Delta f_{SB}/f_0$ as a function of impedance ratio K using (2).

FIGURE 3: Variation of electric length in degree θ_0 as a function of impedance ratio K using (3).

$13.5 f_0$ using (2). The electrical length θ_0 of the SIR can be determined as

$$\left(Z_p^2 \cdot \cos \theta_0 - Z_s^2 \cdot \tan \theta_0 \right) \sin \theta_0 + Z_s \cdot Z_p \cos \theta_0 - Z_s = 0 \quad (3)$$

where $\theta_s = \theta_p = \theta_0$ is assumed. From the relationship in Figure 3, it can be observed that the resonator length (θ_0) can be shortened by selecting a smaller impedance ratio value K (or bigger impedance difference), enabling a compact-size resonator.

2.2.2. Two-Hairpin SIR. A NBPf with a 4–6% fractional bandwidth can be designed with two cascaded SIRs. Figure 4(a) illustrates the cross-sectional view of the proposed SIR NBPf implemented in SSL. The substrate for the

FIGURE 4: Proposed NBPf with two cascaded hairpin SIRs in SSL: (a) cross-sectional view of the SSL and (b) planar circuit view of two hairpin SIR structures.

filter circuit was RO4003 with dielectric constant $\epsilon_r = 3.38$ and thickness of $h = 0.305$ mm. The height of the metal cover is chosen as $b = 0.525$ mm.

Figure 4(b) shows a planar circuit layout view of the two cascaded hairpin SIR structures for the proposed NBPf. The proposed filter has the passband center frequency of $f_0 = 0.75$ GHz with a fractional frequency bandwidth of 5% and the Chebyshev passband ripple of 0.1 dB. With the impedance ratio of $K = 0.015$, the electrical length of the low-impedance coupled line and high-impedance line of the SIR is calculated as $\theta_0 = 15^\circ$ using (3). Because the hairpin SIR gaps face each other, the cascaded SIR NBPf has electromagnetic (EM) coupling. The EM coupling coefficients between two hairpin SIRs can be obtained as a function of the coupling spacing s as described in [9]. Figure 5 shows three coupling coefficients as a function of the coupling spacing s . Among three coupling coefficients, the electric coupling coefficient was used for the design to minimize coupling spacing s . With a 5% fractional bandwidth, the coupling coefficient becomes 0.052, and the corresponding coupling spacing s is determined as $s = 0.4$ mm.

2.3. Design of the MSL-to-SSL Transition. The design guideline of the ultrawideband MSL-to-SSL transition was proposed by the author's group [7]. This transition is particularly useful due to the possibility of easy integration with MSL-based circuits. The layout views of the transition circuit structure for the top and bottom sides are shown in Figure 6(a), and the cross-sectional views of the transition

FIGURE 5: Three coupling coefficients as a function of the coupling spacing s .

stages with simplified configurations of the electric field distributions are shown in Figure 6(b). The characteristic impedance at each section of the proposed transition is kept at 50Ω to have a wide bandwidth. The transition consists of transitional structures between MSL and SSL. In the MSL portion, the electric field lines are perpendicularly terminated at the ground plane of the substrate (A–A') in Figure 6(b). In the SSL portion, the electric field lines are shaped to form a TEM field between the signal line and metal wall (D–D'). In order to gradually match the field distributions between MSL and SSL, a transitional structure of a shielded CBCPW (conductor-backed coplanar waveguide) (B–B') with the cover cavity is placed after the MSL section (A–A'). The electric field lines of the transition structure tend to possess increased horizontal components which are terminated at the edge of the cover (B–B'). As the width of the aperture on the bottom conductor of the substrate (C–C') gradually widens, the electric field lines flow out of the bottom aperture and terminate at the edge of the bottom carrier housing. The width of the top conductor is also changed along the transition to match the characteristic impedance and to provide smooth field transformation toward SSL. For the optimal transition structure, the size of the cover cavity and bottom cavity are kept the same as that of the SSL. The electric field lines are smoothly transformed from MSL to SSL. Figure 7 shows simulated and measured results of the fabricated MSL-to-SSL transition. The measured insertion loss of the transition is less than -0.7 dB from near DC to 10 GHz.

3. Simulation and Measurements

Figure 8(a) shows a picture of the planar circuit view of the filter with two cascaded hairpin SIRs, and Figure 8(b) is a picture of the perspective view of the SSL NBPF module with the metal cover. The design parameters of the proposed SIR

FIGURE 6: Proposed MSL-to-SSL transition: (a) top and bottom views and (b) cross-sectional views of simplified electric field distributions.

NBPF in Figure 4(b) are as follows: $g = 0.3$ mm, $s = 0.6$ mm, $l_1 = 12.44$ mm, $l_2 = 17.72$ mm, $l_3 = 7.6$ mm, $w_1 = 0.82$ mm, and $w_2 = 6.5$ mm. The size of the fabricated hairpin SIR filter excluding the feedline is 17.72 mm $\times$ 12.44 mm.

Figures 9(a) and 9(b) show the simulated and measured S-parameters for the proposed SSL NBPF. The harmonic suppression bandwidth can be verified from Figure 9(a): that is, $\Delta f_{SB} = 9.35$ GHz ($\Delta f_{SB} = 13.5 f_0$) from 0.75 GHz to 10.1 GHz. As shown in Figure 9(b), the passband insertion loss was only -0.9 dB with 5% of the narrow bandwidth. This low passband insertion loss was due to SSL properties, where most of the signal propagates through the air and the radiation loss is minimized due to the metallic waveguide structure.

FIGURE 7: Fabricated MSL-to-SSL transition: simulation and measurement results.

(a)

(b)

FIGURE 8: Pictures of the fabricated SSL NBPF: (a) without the metal cover and (b) with the metal cover.

Table 1 compares the performance of the proposed SSL NBPF with those of the previous published results of the NBPFs with broadband harmonic suppression. It is noted that, for comparison, only narrow bandpass filters (<10% bandwidth) with harmonic suppression are considered. The proposed SSL NBPF with two cascade SIRs demonstrates excellent performance in harmonic suppression bandwidth, insertion loss, and narrow fractional bandwidth, well surpassing the results of the previous reports.

(a)

(b)

FIGURE 9: Simulation and measurement results of the fabricated SSL NBPF: (a) whole frequency range and (b) near passband frequency.

4. Conclusion

In this paper, a design method for the 4–6% narrow bandpass filters (BPFs) with wide harmonic suppression bandwidth is described. The proposed filter consists of two cascaded hairpin step impedance resonators (SIRs) in a suspended stripline (SSL). As an example of the proposed design method, a low-loss NBPF with a 5% bandwidth with wide-band harmonic passband suppression up to $13.5 f_0$ has been demonstrated. The proposed design utilized the property of a suspended stripline (SSL) which has a much bigger impedance ratio than that of a microstripline (MSL) to have wide-band harmonic suppression. The proposed BPF is a compact and high-performance filter, which can be easily integrated with microstripline-based circuits. Therefore, the proposed filter can be applicable to various wireless communication systems, multiband systems, and duplexers, and the passband center frequency can be extended up to mm-wave frequency.

TABLE 1: Performance comparison of the proposed filter with the previously developed harmonic-suppressed NBPFs.

Ref.	Center freq (GHz)	Fractional bandwidth (%)	Insertion loss (dB)	Harmonic suppression Δf_{SB}
[1]	1.5	7	1.4	22 dB up to $5.2 f_0$
[2]	1.92	8	0.75	20 dB up to $1.8 f_0$
[3]	1.63	9	0.66	25 dB up to $3 f_0$
[4]	2.0	3.3	2.9	20 dB up to $3.2 f_0$
[5]	1.9	4	2.5	20 dB up to $1.8 f_0$
This work	0.75	5	0.9	22 dB up to $13.5 f_0$

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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