Compact Dual-band BPF Composed of \( LC \ J \)-inverters Using Lumped Elements

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Abstract
A compact dual-band bandpass filter (DB-BPF) composed of chip and patterned lumped elements is realized. Two types of dual-band \( LC \ J \)-inverters are proposed for DB-BPF design. Also, a large amount of attenuation between two BPF characteristics is realized by the effects of the proposed dual-band \( LC \ J \)-inverters. The fabricated DB-BPF has both good isolation characteristics and compact size.

Keywords: Dual-band bandpass filter (DB-BPF), Compact DB-BPF, DB-BPF synthesis, Lumped element, Dual-band \( LC \ J \)-inverter

1. Introduction
In wireless communication systems, as the amount of data being communicated is larger, more frequency bands or broader frequency bandwidth are required. A carrier aggregation (CA) technique has been used for acquiring broad frequency bandwidth in rare frequency environments. Although many bandpass filters (BPFs) and switches have been used in wireless communication devices for realizing the CA technique, the sizes of them are predicted to reach their limit.

A compact dual-band bandpass filter (DB-BPF) is an effective circuit for downsizing radio frequency (RF) frontends. Significant research has been done for compact DB-BPFs; however, there have been few studies in which the DB-BPFs have both high isolation characteristics between two channels and compact size. Compact DB-BPFs with high isolation characteristics using spiral-shaped stepped impedance resonators (SIRs)[1] and folded SIRs[2] are shown. It has been found that SIR is a key technology for satisfying the need for both the isolation characteristic and compact size; though, in order to be more miniaturized, it is necessary to consider other resonator candidates. Microstrip line (MSL) and coplanar waveguide (CPW) types of compact spiral resonators are employed for DB-BPF,[3] however, they are difficult to use, with the exception of a superconductor material, because a multi-turned spiral resonator composed of thin conductor lines causes high insertion loss. Recently, a dual-band matching network using lumped elements for DB-BPF design is shown. [4] This approach satisfied the need for both low insertion loss and a downsized circuit area. Chip or other types of lumped elements are good candidates for realizing a compact DB-BPF if higher isolation characteristics are achieved.

In this paper, we attempt to realize a compact DB-BPF with high isolation characteristics between two BPF characteristics using lumped elements. First, synthesis of the DB-BPF is explained. We propose new \( J \)-inverters which are composed of lumped elements and operate in two frequency bands. Next, the circuit structure is configured using chip and copper-foil-patterned lumped elements. Finally, the measured frequency characteristics of the fabricated DB-BPF are shown.

2. Circuit Synthesis of DB-BPF
Figure 1 shows a flow chart for DB-BPF design. Although it is similar to the general DB-BPF design procedure, our results are characterized by the elements taken from \( J \)-inverters and circuit structure designs.

There are many synthesis methods for DB-BPFs based on a coupling matrix[4–11] or \( K \)- or \( J \)-inverters.[12–15] Those are excellent methods when a DB-BPF structure is configured using series or parallel resonators, external quality factor \( Q_e \) and coupling coefficient \( k_{ij} \) \((i, j = 1 \text{ to } N)\),
where \( N \) shows the number of resonators; however, this is not always good in cases with a DB-BPF design using chip or patterned lumped elements. A DB-BPF made by lumped elements must directly transform a prototype lowpass filter (LPF) into the DB-BPF. The following frequency transformation equation for a multi-band BPF is proposed:[16]

\[
\Omega = \frac{\omega}{A_1} - \frac{B_1}{\omega} - \sum_{i=2}^{M} \frac{1}{\frac{\omega}{A_i} - \frac{B_i}{\omega}}.
\]  

(1)

Especially for \( M = 2 \), namely DB-BPF (\( M \) means the number of passbands),

\[
\Omega = \frac{\omega}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}}.
\]  

(2)

where \( \Omega \) and \( \omega \) show the angular frequency for a prototype DB-BPF and the real angular frequency for a DB-BPF, respectively. The prototype DB-BPF is based on a prototype LPF.[17] In the case of the prototype LPF, the prototype angular frequencies of a passband, a cutoff and a rejection band are \( 0 \leq \Omega \leq 1 \), \( \Omega = 1 \) and \( \Omega > 1 \), respectively. Also, \( A_1, B_1, A_2 \) and \( B_2 \) show the unknown constants and can be solved for by considering four boundary conditions for a DB-BPF.

The relationships among \( \Omega, \omega_1, \omega_2, \omega_3 \) and \( \omega_4 \) (\( \omega_1 < \omega_2 < \omega_3 < \omega_4 \)) are as follows:

\[
\begin{align*}
\Omega &= -1 = \frac{\omega_1}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}} \\
\Omega &= 1 = \frac{\omega_2}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}} \\
\Omega &= -1 = \frac{\omega_3}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}} \\
\Omega &= 1 = \frac{\omega_4}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}}
\end{align*}
\]  

(3)  

(4)  

(5)  

(6)

where \( \omega_1, \omega_2, \omega_3 \) and \( \omega_4 \) show the desired edge angular frequencies for each BPF. In the case of the Chebyshev type, those are defined as two edge angular frequencies, which are equal to the passband ripple of \(|S_{21}|\). While, in the case of the Butterworth type, those are shown to be two edge angular frequencies, which are equal to 3 dB degrading from maximum \(|S_{21}|\). When Eqs. (3) to (6) are solved for \( A_1, B_1, A_2 \) and \( B_2 \), those are shown as follows:

\[
A_1 = \omega_2 - \omega_1 + \omega_4 - \omega_3,
\]  

(7)

\[
B_1 = \frac{\omega_1\omega_2\omega_3\omega_4}{\omega_1\omega_2(\omega_1 - \omega_3) + \omega_3\omega_4(\omega_2 - \omega_1)}.
\]  

(8)

\[
A_2 = \frac{(\omega_2 - \omega_1)(\omega_3 - \omega_4)(\omega_3 + \omega_4)(\omega_1 + \omega_2)(\omega_4 - \omega_1)(\omega_3 - \omega_2)(\omega_4 - \omega_3)(\omega_3 - \omega_4)}{\omega_1\omega_2(\omega_1 - \omega_2) + \omega_4\omega_3(\omega_2 - \omega_1)}.
\]  

(9)
\[
B_2 = \frac{(\omega_2 - \omega_1) + \omega_3 (\omega_2 - \omega_3)^2 (\omega_2 - \omega_1 + \omega_3)}{(\omega_2 - \omega_1)(\omega_3 - \omega_1) (\omega_2 + \omega_1)(\omega_3 + \omega_1) (\omega_1 - \omega_2)(\omega_3 - \omega_2)_1}
\]

(10)

Figures 2 and 3 show the relationship between the elements for prototype LPF and DB-BPF resonators. \(g_L, g_c, Z_0\) and \(G_0\) show inductive and capacitive \(g\)-parameters of the prototype LPF,[17] impedance and admittance, which are normally 50 \(\Omega\) and 0.02 S, in the filter. Figure 4 shows the circuit schematic of a third-order DB-BPF. The values of each inductor and capacitor in Fig. 4 are calculated as:

\[
Z_{\text{in}} = Z_{\text{out}} = \frac{1}{G_{\text{in}}} = \frac{1}{G_{\text{out}}},
\]

(11)

\[
L_{S11} = L_{S31} = \frac{g_L Z_0}{A_1},
\]

(12)

\[
C_{S11} = C_{S31} = \frac{1}{B_1 g_L Z_0},
\]

(13)

3. Dual-band LC J-inverters

When a printed circuit board (PCB) made of two copper foil layers is employed for configuring a lumped element-type DB-BPF, the circuit size is large, caused by the arrangement of the series \(LC\) resonators, which are \(L_{S11}, C_{S11}, L_{S31}\) and \(C_{S31}\), shown in Fig. 4. Therefore, it is necessary to transform the circuit using \(K\)- or \(J\)-inverters. Normal \(K\)- and \(J\)-inverters work as impedance and admittance inverters. For example, a series-connected inductor which is sandwiched by two \(K\)- or \(J\)-inverters changes to a parallel-connected capacitor [17, pp. 113–128]. In contrast, a parallel-connected inductor changes to series-connected capacitor. However, normal \(K\)- or \(J\)-inverters cannot be used for transformation of a lumped element-type DB-BPF because those are for a single-band BPF. Therefore, two types of dual-band \(J\)-inverters are proposed.

3.1 Dual-band LC J-inverter between dual-band resonators

Figure 5 shows a dual-band LC \(J\)-inverter between dual-band resonators. A dual-band LC \(K\)-inverter can also introduce using same concept by considering impedances between them. \(L_{\text{inv}}, C_{\text{inv}}\) show the inductance and capacitance in the dual-band LC \(J\)-inverter, which is defined as type 1. First, \(\omega_1\) and \(\omega_2\) (\(\omega_1 < \omega_2\)) are calculated by

\[
L_{S12} = L_{S32} = \frac{g_L Z_0}{B_2},
\]

(14)

\[
C_{S12} = C_{S32} = \frac{1}{A_2 g_L Z_0}.
\]

(15)

\[
L_{P21} = \frac{1}{B_1 g_C Z_0},
\]

(16)

\[
C_{P21} = \frac{g_C G_0}{A_1},
\]

(17)

\[
L_{P22} = \frac{1}{A_2 g_C Z_0}.
\]

(18)

\[
C_{P22} = \frac{g_C G_0}{B_1}.
\]

(19)

**Fig. 2** An inductor for prototype LPF and dual-band resonators.

**Fig. 3** A capacitor for prototype LPF and dual-band resonators.

**Fig. 4** Circuit schematic of a third-order DB-BPF.

**Fig. 5** Dual-band LC \(J\)-inverter (type 1).
solving the following equations:

\[ J = \pm \left( \alpha C_{\text{inv}} - \frac{1}{\omega L_{\text{inv}}} \right), \quad (20) \]

\[ \omega_{r1} = -\frac{J L_{\text{inv}} + \sqrt{J^2 L_{\text{inv}}^2 + 4 J L_{\text{inv}} C_{\text{inv}}}}{2 C_{\text{inv}}}, \quad (21) \]

\[ \omega_{r2} = \frac{J L_{\text{inv}} + \sqrt{J^2 L_{\text{inv}}^2 + 4 J L_{\text{inv}} C_{\text{inv}}}}{2 C_{\text{inv}}}, \quad (22) \]

\[ \omega_{o} = \sqrt{\omega_{r1}\omega_{r2}}. \quad (23) \]

Next, from solving Eqs. (21), (22) and (23),

\[ C_{\text{inv}} = \frac{J}{\omega_{r2} - \omega_{r1}}, \quad (24) \]

\[ L_{\text{inv}} = \frac{\omega_{r2} - \omega_{r1}}{\omega_{o}^2}. \quad (25) \]

\( \omega_{r1} \) and \( \omega_{o} \) are consistent with \( \sqrt{\omega_{r1}\omega_{o2}} \) and \( \sqrt{\omega_{r2}\omega_{o1}} \) when a DB-BPF is designed.

### 3.2 Dual-band LC J-inverter between a dual-band resonator and input or output load

The frequency characteristics in a case where a dual-band LC J-inverter is placed between \( Z_{\text{in}} \) or \( Z_{\text{out}} \) and a dual-band resonator, as shown in Fig. 5, are degraded. Thus, another type of dual-band LC J-inverter is proposed. Figure 6 shows a dual-band LC J-inverter, designed as type 2, which is placed between a dual-band resonator and an input or output load. A dual-band LC J-inverter can also introduce using same concept by considering impedances between them.

\( L_{\text{p1inv}}, L_{\text{p2inv}}, C_{\text{p1inv}} \) and \( C_{\text{p2inv}} \) show the inductances and capacitances, respectively, in the type 2 dual-band LC J-inverter. First, \( \omega_{o1} \) and \( \omega_{o2} \) \((\omega_{o1} < \omega_{o2})\) are calculated by solving the following equations:

\[ Y_{\text{p1inv}}(\omega) = j \omega C_{\text{p1inv}} + \frac{1}{j \omega L_{\text{p1inv}}}, \quad (26) \]

\[ Y_{\text{p2inv}}(\omega) = -j \omega C_{\text{p2inv}} - \frac{1}{j \omega L_{\text{p2inv}}}. \quad (27) \]

Introducing input admittance \( Y_{\text{in}} \) from the right side of Fig. 6,

\[ Y_{\text{in}} = Y_{\text{p2inv}} + \frac{G Y_{\text{p1inv}}}{Y_{\text{p1inv}} + G} = \frac{G (Y_{\text{p1inv}} + Y_{\text{p2inv}}) + Y_{\text{p1inv}} Y_{\text{p2inv}}}{Y_{\text{p1inv}} + G}, \quad (28) \]

Considering the relationship between \( Y_{\text{in}} \) and the \( f \)-inverter,

\[ Y_{\text{in}} = \frac{f^2}{G_{\text{in}}}, \quad (29) \]

Also, using the conditions of \( \text{Re} \{Y_{\text{in}}\} = f^2/G_{\text{in}} \) and \( \text{Im} \{Y_{\text{in}}\} = 0, \)

\[ \text{Re} \left\{ \frac{G (Y_{\text{p1inv}} + Y_{\text{p2inv}}) + Y_{\text{p1inv}} Y_{\text{p2inv}}}{Y_{\text{p1inv}} + G} \right\} = f^2/G_{\text{in}}, \quad (30) \]

\[ \text{Im} \left\{ \frac{G (Y_{\text{p1inv}} + Y_{\text{p2inv}}) + Y_{\text{p1inv}} Y_{\text{p2inv}}}{Y_{\text{p1inv}} + G} \right\} = 0. \quad (31) \]

Solving Eqs. (30) and (31) for \( \omega, \)

\[ \omega_{o1} = \frac{-D}{C_{\text{p1inv}}} \left( \frac{D}{C_{\text{p1inv}}} \right)^2 + \frac{4}{L_{\text{p1inv}} C_{\text{p1inv}}} \quad (32) \]

\[ \omega_{o2} = \frac{-D}{C_{\text{p2inv}}} \left( \frac{D}{C_{\text{p2inv}}} \right)^2 + \frac{4}{L_{\text{p2inv}} C_{\text{p2inv}}} \quad (33) \]

\( \omega_{o1} \) and \( \omega_{o2} \) are consistent with \( \sqrt{\omega_{o1}\omega_{o2}} \) and \( \sqrt{\omega_{o2}\omega_{o1}} \) when a DB-BPF is designed.

Here,

\[ D = \frac{G_{\text{in}} f^2}{G_{\text{in}}^2 - f^2} (\because G > f). \quad (34) \]

Finally, solving Eqs. (32) and (33) for \( L_{\text{p1inv}}, C_{\text{p1inv}}, L_{\text{p2inv}}, \) and \( C_{\text{p2inv}}, \)

\[ L_{\text{p1inv}} = \frac{\omega_{o2} - \omega_{o1}}{D \omega_{o2} \omega_{o1}}, \quad (35) \]

\[ C_{\text{p1inv}} = \frac{D}{\omega_{o2} - \omega_{o1}}, \quad (36) \]

\[ L_{\text{p2inv}} = \frac{\omega_{o2} - \omega_{o1}}{F \omega_{o2} \omega_{o1}}, \quad (37) \]

\[ C_{\text{p2inv}} = \frac{F}{\omega_{o2} - \omega_{o1}}, \quad (38) \]

\[ F = \frac{G_{\text{in}}^2 D}{G_{\text{in}}^2 + D^2}. \quad (39) \]

### 4. Circuit Design of DB-BPF

Table 1 shows the design specifications for a DB-BPF. The DB-BPF design is based on the method shown in section 3. Tables 2 and 3 show the values calculated from Eqs. (7) to (19). Figure 7 shows the calculated frequency characteristics from a circuit simulator. Advanced Design System (ADS) is used as the circuit simulator. Also, a transformed circuit using dual-band \( LC J \)-inverters and circuit
The values of all \( J \)-inverters are equal to 0.01 S. \( L_{p11}, C_{p11}, \) \( L_{p12}, C_{p12}, L_{p31}, C_{p31}, \) and \( C_{p32} \) show transformed circuit elements by \( J \)-inverters. Figure 9 shows the frequency characteristics for the transformed circuits. \( L'_{p11}, \) \( C'_{p11}, \) \( L'_{p12}, C'_{p12}, L'_{p31} \) and \( C'_{p32} \) are calculated using Eqs. (35) to (39). A transmission zero around 3.54 GHz appears as a result of the dual-band \( LC \) \( J \)-inverters. Consequently, a large amount of attenuation at \( \omega_0 \), which is more than 200 dB, is acquired. In the next section, a circuit structure and simulated results from an electromagnetic simulator are shown.

**Table 1** Design specifications.

| Parameter          | low-band | high-band |
|--------------------|----------|-----------|
| Center frequency (GHz) | 2.399    | 5.194     |
| Fractional bandwidth \( F\text{BW} \) | 0.05     | 0.1       |
| Passband ripple (dB)  | < 0.1    | < 0.1     |

**Table 2** Calculated values from Eqs. (7)–(10).

| Parameter | Value               |
|-----------|---------------------|
| \( \omega_1 \) (rad/s) | \( 1.470 \times 10^{10} \) (2.34 GHz) |
| \( \omega_2 \) (rad/s) | \( 1.546 \times 10^{10} \) (2.46 GHz) |
| \( \omega_3 \) (rad/s) | \( 3.104 \times 10^{10} \) (4.94 GHz) |
| \( \omega_4 \) (rad/s) | \( 3.431 \times 10^{10} \) (5.46 GHz) |
| \( \omega_0 \) (rad/s) | \( 2.218 \times 10^{10} \) (3.53 GHz) |
| \( A_1 \) (rad/s) | \( 3.431 \times 10^9 \) |
| \( B_1 \) (rad/s) | \( 1.565 \times 10^{11} \) |
| \( A_2 \) (rad/s) | \( 6.855 \times 10^{10} \) |
| \( B_2 \) (rad/s) | \( 4.021 \times 10^9 \) |

**Table 3** Circuit elements in Fig. 4.

| Parameter | Value |
|-----------|-------|
| \( Z_{in} = Z_{out} \) (Ω) | 50    |
| \( L_{111} = L_{331} \) (nH) | 12.83 |
| \( C_{111} = C_{331} \) (pF) | 0.1238|
| \( L_{412} = L_{422} \) (nH) | 9.2   |
| \( C_{412} = C_{422} \) (pF) | 0.2828|
| \( L_{211} \) (nH) | 0.2783 |
| \( C_{211} \) (pF) | 5.707  |
| \( L_{222} \) (nH) | 0.6357 |
| \( C_{222} \) (pF) | 4.093  |

**Table 4** Circuit elements in Fig. 8.

| Parameter | Value |
|-----------|-------|
| \( Z_{in} = Z_{out} \) (Ω) | 50    |
| \( L_{p11} \) (nH) | 3.092 |
| \( C_{p11} \) (pF) | 0.6563|
| \( L'_{p11} = L'_{p31} \) (nH) | 3.508 |
| \( C'_{p11} \) (pF) | 0.222 |
| \( L'_{p12} = L'_{p32} \) (nH) | 2.828 |
| \( C'_{p12} \) (pF) | 0.92  |
| \( L_{s11} \) (nH) | 3.571 |
| \( C_{s11} \) (pF) | 0.5684|
| \( L_{s12} \) (nH) | 0.3297|
| \( C_{s12} \) (pF) | 4.57  |
| \( L_{s22} \) (nH) | 0.6357|
| \( C_{s22} \) (pF) | 4.093 |
5. Circuit Structure of DB-BPF Using Chip Lumped Elements

Figure 10 shows a first circuit structure of a DB-BPF. A microstrip line (MSL) structure is assumed. The DB-BPF is configured using chip and copper-foil-patterned lumped elements. Table 5 shows the lumped elements for configuring the DB-BPF. The inductors form by high impedance copper foil patterns, since this DB-BPF is strongly affected by the sensitivities of inductors. The relative dielectric constant $\varepsilon_r$, $\tan\delta$ and the thickness of the dielectric substrate are 3.2, 0.001, and 0.5 mm, respectively. Also, the conductivity and thickness of the conductor are $5.8 \times 10^7$ S/m and 18 $\mu$m, respectively. The size of the chip capacitor is equal to $0.5 \times 1.0$ mm. GJM1555C series chip capacitors made by Murata Manufacturing Co., Ltd. were selected.[18] S-parameter data in Touchstone formats for chip capacitors are employed when the DB-BPF are configured using an electromagnetic (EM) simulator. The frequency characteristics calculated by the EM simulator are shown in Fig. 11. Sonnet is used for the EM simulator. Those results are degraded compared with those from circuit simulation. The causes are unwanted parasitic inductances and capacitances from land patterns and chip elements. These parasitic elements are compensated, since it is difficult to remove them. As trial and error, it is found that influences of $L'_{p11}$ ($L'_{p31}$), $L'_{p12}$ ($L'_{p32}$) and $C'_{p12}$ ($C'_{p32}$) against frequency characteristics of Fig. 11 are dominant. It is necessary to optimize them by increasing total lengths of $L'_{p11}$ ($L'_{p31}$)
and \( L'_{p12} \) and \( L'_{p32} \) and the capacitance of \( C'_{p12} \) \( (C'_{p32}) \). Figure 12 and Table 6 show the optimized circuit structure and the parameters of the DB-BPF. The EM simulated results in Fig. 13 are almost in good agreement with those from circuit simulation.

### Table 6: Explanation of circuit elements in Fig. 12.

| Parameter          | Model number or type | Value or total length |
|--------------------|----------------------|-----------------------|
| \( L_{\text{pin}} \) (nH) | GJM1555C1HR80WB01D   | 0.6 ± 0.05 pF         |
| \( L_{p11} \)         | GJM1555C1HR10WB01D   | 0.1 ± 0.05 pF         |
| \( L'_{p11} \) = \( L'_{p31} \) (nH) | GJM1555C1H3R8BB01D   | 3.8 ± 0.1 pF          |
| \( L'_{p12} \) = \( L'_{p32} \) (nH) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{p11} \) \( = C_{p31} \) (pF) | GJM1555C1H3R8WB01D   | 0.3 ± 0.05 pF         |
| \( C_{p12} \) \( = C_{p32} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( L_{\text{inv}} \) (nH) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( L_{\text{inv}} \) (nH) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( L_{\text{inv}} \) (nH) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |
| \( C_{\text{inv}} \) (pF) | GJM1555C1HR30WB01D   | 0.3 ± 0.05 pF         |

### 6. Fabrication and Measurement of DB-BPF Using Chip Lumped Elements

Figure 14 shows a photograph of the fabricated DB-BPF. Copper foil patterns are fabricated using a PCB prototyping machine. After its process, chip capacitors and SMA connectors are soldered by hand. Figures 15 and 16 show the measured frequency characteristics. Also, Table 7

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Fig. 16  Expanded frequency characteristics around passbands of Fig. 15.

Table 7  Comparison with frequency characteristics.

| Parameter                  | Circuit simulation | Measured results |
|----------------------------|--------------------|------------------|
|                            | low-band           | high-band        |
| Center frequency (GHz)     | 2.4                | 5.19             |
| FBW                        | 0.05               | 0.1              |
| (3 dB BW)                  | 0.069              | 0.131            |
| Insertion loss (dB)        | lossless           | lossless         |
| Return loss (dB)           | 16.9               | 17.3             |

Table 8  Benchmarking of DB-BPF.

| Ref. | Center frequency (GHz) | Center frequency of DB-BPF (GHz) | FBW | Insertion loss (dB) | Maximum isolation (dB) | 40-dB isolation bandwidth (GHz) | 40-dB isolation FBW | Normalized area by \( \lambda^2 \) |
|------|------------------------|----------------------------------|-----|---------------------|------------------------|---------------------------------|---------------------|-------------------------------|
|      | low-band               | high-band                        |     |                     |                        |                                 |                     |                               |
| [1]  | 1.58                   | 2.4                              | 1.944| 0.06                | 1.1                    | 55                              | 0.208               | 0.107                         | 0.175                        |
| [2]  | 1.57                   | 5.2                              | 2.837| 0.034               | 1.78                   | 1.39                            | 65.2                | 1.904                         | 0.666                         | 0.014                        |
| [3]  | 1.8                    | 2.4                              | 2.078| 0.059               | 0.1                    | 0.13                            | >75                 | 0.343                         | 0.165                         | 0.008                        |
| [7]  | 2.43                   | 5.26                             | 3.575| 0.123               | 1.86                   | 3.42                            | 52                  | 1.030                         | 0.288                         | 0.008                        |
| [13] | 20.0                   | 21.0                             | 20.5 | 0.015               | 1.37                   | 1.1                             | 59                  | 0.163                         | 0.008                         | 1.158                        |
| [14] | 1.05                   | 1.29                             | 1.168| 0.066               | 1.48                   | 1.35                            | 50.6                | 0.022                         | 0.019                         | 0.166                        |
| [15] | 1.85                   | 2.85                             | 2.206| 0.119               | 1.2                    | 2.1                             | 45.5                | 0.055                         | 0.024                         | 0.096                        |
| [19] | 0.924                  | 1.79                             | 1.287| 0.097               | 2.4                    | 1.92                            | 55                  | 0.062                         | 0.048                         | 0.014                        |
| [20] | 2.45                   | 5.7                              | 3.737| 0.107               | 1                      | 1.2                             | 55.5                | 0.304                         | 0.081                         | 0.004                        |
| [21] | 2.43                   | 5.26                             | 3.575| 0.123               | 1.86                   | 3.42                            | 52                  | 1.030                         | 0.288                         | 0.008                        |
| [22] | 0.61                   | 1.36                             | 0.911| 0.323               | 0.45                   | 0.75                            | 60                  | 0.195                         | 0.214                         | 0.011                        |
| [23] | 0.9                    | 1.75                             | 1.255| 0.42                | 0.2                    | 0.5                             | 48                  | 0.069                         | 0.055                         | 0.022                        |
| [24] | 2.37                   | 29.84                            | 8.410| 0.194               | 0.75                   | 1.74                            | 23                  | 24.97                         | 2.969                         | 0.074                        |
| [25] | 8                      | 11.4                             | 9.550| 0.030               | 2.26                   | 3.07                            | >50                 | 2.396                         | 0.251                         | 2.175                        |
| [26] | 13.7                   | 19.1                             | 16.17| 0.023               | 3.5                    | 3.1                             | 58                  | 3.440                         | 0.213                         | 1.184                        |
| This work                  | 2.4                   | 5.15                             | 3.516| 0.069               | 4.2                    | 2.1                             | 73.5                | 1.837                         | 0.522                         | 0.022                        |
shows a comparison between the design specifications and EM simulated results. Although the return loss is worse than that from circuit simulation, because of the tolerances of lumped elements, dual-band characteristics are acquired. Insertion losses are calculated by circuit simulation considering the equivalent series resistances (ESRs) of each inductor and capacitor. Those are almost in good agreement with the measured ones. The physical size is $11.45 \times 12 \text{ mm}^2$. The normalized size by guided wavelength $\lambda_g$ at the center frequency of 2.4 GHz in the low band is $0.146 \times 0.153 \lambda_g^2$.

Table 8 shows benchmarking of the DB-BPF. From a technical point of view for a DB-BPF, the isolation characteristics mean the amount of attenuation between two BPF characteristics. The parameters of 40-dB isolation bandwidth and 40-dB isolation FBW show a frequency width and fractional bandwidth with isolation characteristics above 40 dB. The proposed DB-BPF has both the features of compact size and good isolation. The size of the proposed DB-BPF could become more compact by improving the layout. Those advantages are obtained by the two proposed types of dual-band LC inverters with circuit structures composed of chip and patterned lumped elements.

7. Conclusion

A compact dual-band bandpass filter (DB-BPF) using chip and patterned lumped elements was realized. This was thanks to the two types of proposed dual-band LC $J$-inverters. Also, a large amount of attenuation between two BPF characteristics was realized by the effects of the proposed dual-band LC $J$-inverters. Although it was necessary to remove the effects of lumped element tolerances and to re-design the layout, a compact DB-BPF with a good frequency characteristic was realized.

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