1. Introduction

There are two kinds of frequency dividers for wireless communication. One is a duplexer, which enables division of the receiver and transmitter frequencies. It requires the miniaturization of the circuit structure and the characteristics of low insertion loss (IL), high isolation (Iso) between receiver and transmitter, and high power capability. Another kind is a diplexer, which enables division of the frequencies between wireless systems. It is called a multiplexer when the operating frequencies are over two kinds of wireless systems. It requires downsizing of the circuit structure and realizing characteristics of low IL, low reflection, high Iso and sharp rejection. The common demands on duplexers and diplexers are division of some operation frequencies, downsizing the circuit structure, and realizing high Iso. The high Iso characteristics are especially significant for both circuits since the transmitted power in the case of a duplexer or the noise and the distortion in the case of a diplexer are problems.

In previous studies, diplexers have frequently been composed of two BPFs. However, in BPF-BPF diplexers, the bandwidth (BW) for each channel is limited to a narrow passband. Therefore, LPF-BPF or LPF-HPF diplexers, which are composed of an LPF and a BPF or an HPF, are proposed. LPF-BPF or LPF-HPF diplexers have certain advantages, namely, broadband characteristics and a lower IL than normal diplexers using two BPFs. An LPF-HPF diplexer has broader frequency band characteristics and a lower IL than an LPF-BPF diplexer. Lee et al. improved the Iso characteristics between two channels with a circuit that is composed of a BPF with a broad passband and an LPF-HPF diplexer with attenuation poles. Although high Iso characteristics of more than 45 dB were realized by effectively setting attenuation poles, there are some cases for which that is insufficient to satisfy design specification. There is the possibility of acquiring high rejection and suppression characteristics with an integrated high-order LPF-HPF diplexer and two BPFs, as shown in Fig. 1 (c). Higher-order LPF-HPF diplexers tend to be large when LPF-HPF diplexers are composed of distributed transmission lines. Nowadays, commercial chip inductors and capacitors have a lower tolerance for element value, lower equivalent series resistance (ESR), higher self-resonant frequency (SRF), and a smaller size than previous ones. There has been no literature on using chip elements for realization of an LPF-HPF diplexer that we know of. It is possible for the frequency characteristics and the size to be compatible by employing chip elements.
In this study, first, the designs of a 2.6-GHz-band LPF and a 5.4-GHz-band HPF are shown. Second, an LPF-HPF diplexer is configured. Normally, the matching circuits between an LPF and an HPF with distributed transmission lines or lumped elements are needed. Our proposed structure has the feature of unifying matching circuits, an LPF and an HPF, since the elements for matching circuits are absorbed in them. The comparison for BPF-BPF diplexers in the cases of using lumped matching circuits, commercial diplexer and our work are shown. Moreover, the benchmarking LPFs, HPFs and LPF-HPF diplexers are shown.

2. Design of LPF and HPF
2.1 Design specifications and selection of chip elements

Table 1 shows the design specifications for an LPF and an HPF. An LPF-HPF diplexer composed of an LPF and an HPF is configured with the low and high bands assumed to be Bluetooth and Wireless LAN (WLAN), respectively. Although it is important for the LPF-HPF diplexer to achieve a low IL and high reflection characteristics (RL), having high Iso characteristics between two channels is more important. The specification for the RL is determined based on the pre-experimental results for the IL of the LPF and HPF, which are less than one-twentieth of the measured transmission losses for them. The LPF and HPF are of the eleventh order since sharp rejection and high Iso characteristics are achieved.

It is also important to select chip capacitors and inductors with the characteristics of low ESR and high SRF. In this study especially, the characteristic of high SRF is needed since the difference between the cutoff frequencies for the LPF and the HPF is more than double. The 1.0 × 0.5-mm ceramic-type capacitors for the GJM series[8] and wire-wound type inductors for the LQW series,[9] made by Murata Manufacturing Co., Ltd., have been selected. S-parameter datum in Touchstone formats for chip capacitors and inductors are employed when the LPF and the HPF are configured using circuit and electromagnetic (EM) simulators.

2.2 Design of LPF with 2.6-GHz cutoff frequency

Figure 2 shows a circuit schematic of a symmetrical eleventh-order T-type LPF. The circuit elements of the LPF are determined by conventional design technique.[10] The ripple characteristic is 0.01 dB. The circuit design and simulation employ the Advanced Design System (ADS) 2015.01. The circuit elements in Fig. 2 are substituted with Touchstone files for chip capacitors and inductors when the circuit structure is configured. The circuit structure is configured using Sonnet 15.52 which is EM simulator. In this study, Panasonic MEGTRON7[11] made of low loss
multi-layer materials is assumed for the design of the LPF and HPF as printed circuit board (PCB). The relative dielectric constant $\varepsilon_r$, $\tan\delta$, substrate thickness, copper foil thickness, and copper conductivity are 3.2, 0.0015, 0.5 mm, 18 $\mu$m and $5.8 \times 10^7$ S/m, respectively. The minimum line and space ($L/S$) are 0.2/0.2 mm, limited by the manufacturing accuracy for a PCB prototype machine. Figure 3 shows a configured circuit structure of eleventh-order LPF using EM simulator and photos of fabricated LPFs in the cases of one capacitor and two capacitors in parallel. Also, the measurement results for fabricated LPFs in the cases of one capacitor and two capacitors in parallel are shown in Fig. 4. Two capacitors in parallel are assumed since there is an SRF of around 6 GHz for a chip capacitor. The SRF enables a shift to a higher frequency by setting two capacitors on a soldering island. It was found that self-resonance is suppressed around 7.5 GHz in Fig. 4. Also, the performance shown in Fig. 4 are high attenuation characteristics in the cut-off band and the design specifications were satisfied.

Li et al.[12] first proposed figure-of-merit (FOM) for an LPF. That became the criteria to show the priority for LPF techniques. The FOM for LPF is defined as follows[12]:

$$FOM = \frac{\xi \cdot RSB \cdot SF}{NCS \cdot AF}.$$  \hfill (1)

where

$$\xi = \frac{\alpha_{\text{max}} - \alpha_{\text{min}}}{f_s - f_c},$$  \hfill (2)

$$RSB = \frac{\text{stopband bandwidth}(-20 \text{dB})}{\text{stopband center frequency}},$$  \hfill (3)

$$SF = \frac{\text{stopband suppression}}{10 \text{dB}} ,$$  \hfill (4)

$$NCS = \frac{\text{physical size (length \times width)}}{\lambda_g} ,$$  \hfill (5)

$$AF = \begin{cases} 1 \text{ (two dimensional design)} \\ 2 \text{ (three dimensional design)} \end{cases}.$$  \hfill (6)

$\xi$ is the roll-off rate. $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ in $\xi$ normally show 40 dB and 3 dB, respectively, which are attenuation quantities of $S_{21}$. And $f_s$ and $f_c$ show the frequencies which $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ acquire, respectively. $RSB$ is the relative stop-band bandwidth. Generally, the frequency responses of an LPF are degraded by harmonic resonances. The criteria for wide cut-off-band suppression characteristics are found by using the $RSB$. $SF$ is the suppression factor, which is the criteria for the maximum attenuation quantity for an LPF on the stop-band. $NCS$ is the normalized circuit size, which is normalized by the guided wavelength $\lambda_g$ at $f_c$. $AF$ is the architecture factor, which is 1 in the case of the planar type, or 2 in the case of three-dimensional structures.

Table 2 shows the benchmarking for LPFs. Although the $FOM$ for our LPF shows a middle level, the circuit square is the smallest compared with other LPFs. Our design will enable more miniaturization by improving the layout design.

2.3 Design of HPF with 5.4-GHz cutoff frequency

The circuit schematic of a symmetrical eleventh-order
T-type HPF is shown in Fig. 5. The HPF circuit elements are determined by a conventional design technique.[10] The ripple characteristic of the HPF is also 0.01 dB. Calculated and configured HPFs also employ the same techniques for an LPF.

Inductors made by a copper foil pattern on the PCB are configured because there are no Touchstone files for chip inductors for HPF design. Parallel inductors are expressed by short-circuited stubs less than \( \frac{\lambda}{4} \), configured as follows:

\[
L = \frac{Z_0 l}{c_0 \sqrt{\varepsilon_{\text{eff}}}},
\]

(7)

where \( L, Z_0, l, \varepsilon_{\text{eff}} \) and \( c_0 \) are inductance, characteristic impedance, stub length, effective dielectric constant of the stub, and light velocity, respectively. The characteristic impedance of a distributed transmission line is determined to be 113.9 \( \Omega \) when the minimum fabricated line width is 0.2 mm. Table 3 shows the inductances and short-circuited stub length of the configured inductors. These dimensions are determined by considering parasitic inductance and capacitance of via and via pad. Figure 6 shows the EM simulation model and fabricated circuit structure. The stub lengths in the circuit structure change after some EM simulations, as shown in Fig. 6. A comparison with EM simulation and measurement results is shown in Fig. 7. They are in almost good agreement with each other and satisfy the design specifications.

Table 4 shows the benchmarking for HPFs. The \( FOMs \) are calculated using the almost same procedure for an LPF except the \( RSB \). The \( RSB \) is defined as the frequency width from DC to \( f_c \) in the case of an HPF. Although the \( FOM \) for our HPF and the \( BW \) for operating an HPF are top-level techniques. Also, the circuit size shows a middle level compared with other HPFs.

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**Table 2** Benchmarking of LPFs.

| \( f_c \) (GHz) | \( \xi \) (dB/GHz) | \( RSB \) | \( SF \) | \( NCS \) | \( AF \) | FOM |
|-----------------|------------------|---------|------|-------|-----|-----|
| [13]            | 0.94             | 881     | 1.388| 2     | 0.0099 | 1    | 259,373 |
| [14]            | 0.82             | 687     | 1.3  | 4.4   | 0.0171 | 1    | 229,804 |
| [15]            | 1.94             | 529     | 1.8  | 2     | 0.011  | 1    | 173,127 |
| [16]            | 1.3              | 600     | 1.013| 3.5   | 0.0168 | 1    | 126,625 |
| [17]            | 1.64             | 189     | 1.69 | 2     | 0.007  | 1    | 91,202  |
| [18]            | 2                | 340     | 1.71 | 3.1   | 0.025  | 1    | 72,094  |
| [19]            | 2.058            | 220     | 1.6  | 2.1   | 0.0148 | 1    | 49,946  |
| [20]            | 1.89             | 72      | 1.86 | 2.4   | 0.009945 | 1 | 32,319  |
| [21]            | 1.357            | 228     | 1.78 | 2.1   | 0.03206 | 1 | 26,583  |
| [22]            | 2.45             | 56.7    | 1.638| 2     | 0.0133 | 1    | 13,966  |
| This work       | 2.599            | 73.8    | 1.255| 4     | 0.004166 | 2 | 44,474  |

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**Table 3** Inductances and short-circuited stub length of the configured inductors in HPF.

| Inductance (nH) | Stub length (mm) |
|-----------------|------------------|
| 2nd and 10th inductors | 1.02 | 1.6 |
| 4th and 8th inductors   | 0.845 | 1.3 |
| 6th inductor          | 0.825 | 1.25 |

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Fig. 5  The circuit schematic of an eleventh-order HPF.

Fig. 6  (a) Configured circuit structure of an eleventh-order HPF, (b) photograph of fabricated HPF.
3. Design and Fabrication of LPF-HPF Diplexer

3.1 Design of LPF-HPF diplexer

The matching circuits between the configured LPF and HPF are required for the LPF-HPF diplexer design. Generally, Π or T types of matching circuits are utilized. It is found that an inductor and a capacitor are enough for matching circuits between an LPF and an HPF after verifying some kinds of matching circuits. Figure 8 shows the configured circuit structure for the LPF-HPF diplexer. An inductor is added on the LPF side while a capacitor is added on the HPF side. As a further advantage, each matching circuit is absorbed in each filter because the first elements of each filter and the elements of the matching circuit are the same. Therefore, the proposed diplexer is downsized. The EM simulation results for the diplexer are shown in Fig. 9. The diplexer has high $I_{iso}$ characteristics of more than 60 dB between both channels. The detail design procedure of matching circuits is referred in.[31]

3.2 Fabrication of LPF-HPF diplexer

Figure 10 shows a photograph of the fabricated LPF-HPF diplexer. A circuit pattern is fabricated by a PCB prototyping machine. Also, all chip elements are soldered by hand. The circuit size is $21 \times 2.4$ mm. The $\lambda_g$ at the LPF cut-off frequency in the case of 50 $\Omega$ for the substrate is equal to 72.67 mm. The normalized area of the diplexer is

| $f_c$ (GHz) | $\xi$ (dB/GHz) | $RSB$ | $SF$ | $NCS$ | $AF$ | $FOM$ | $BW$ (GHz) |
|------------|----------------|------|------|-------|------|-------|------------|
| [23]       | 2.15           | 77.1 | 2.04 | 1.8   | 0.00750 | 1 | 37,740 | 3.85 |
| [24]       | 1              | 87.1 | 0.75 | 4     | 0.00918 | 2 | 14,225 | 4 |
| [25]       | 2.15           | 35.2 | 1.8  | 6     | 0.07600 | 1 | 5,008  | 7.85 |
| [26]       | 1.74           | 34.7 | 1.1  | 5     | 0.03605 | 2 | 2,650  | 6.26 |
| [27]       | 1.8875         | 28.7 | 1.775| 7.8   | 0.09223 | 2 | 2,157  | 2.61 |
| [28]       | 5.67           | 32.0 | 5.04 | 3.95  | 0.16192 | 2 | 1,969  | 15 |
| [29]       | 2.9            | 20.8 | 2.425| 1.775 | 0.12245 | 2 | 366    | 5.1  |
| [30]       | 6.8            | 46.3 | 6.25 | 1.5   | 0.63818 | 2 | 340    | 3.3  |
| This work  | 5.225          | 35.1 | 4.95 | 8.4   | 0.01471 | 2 | 49,566 | 5.77 |

![Fig. 7](image-url) Comparison with EM simulation and measurement of an eleventh-order HPF.

![Fig. 8](image-url) Configured diplexer circuit structure.

![Fig. 9](image-url) EM simulated frequency response of configured diplexer.
Figure 11 shows the frequency responses for EM simulation and measurement results. The main characteristics of the EM simulation and measurement results are shown in Table 5. Although the $I_{so}$ characteristics are worse than in EM simulation, the frequency characteristics of the fabricated LPF-HPF diplexer are in agreement with those in EM simulation.

### 3.3 Comparison of BPF-BPF diplexers characteristics

The frequency characteristics of BPF1 and BPF2 for Bluetooth and WLAN, respectively, are shown in Fig. 12. These frequency characteristics are prepared based on each datasheet.[32, 33] BPF1 and BPF2 are a Film Bulk Acoustic Resonator (FBAR) and multi-layer type, respectively. BPF1 (FBAR)[32] is $1.1 \times 0.9 \times 0.5$ mm$^3$ and BPF2 (multi-layer)[33] is $1.0 \times 0.5 \times 0.45$ mm$^3$. Figure 13 shows the frequency characteristics of a commercial diplexer.[34] The commercial diplexer is $1.6 \times 0.8 \times 0.65$ mm$^3$. Figures 14, 15 and 16 show the system simulation results by circuit simulator based on the circuit in Fig. 1. In Figs. 14 to 16, the color bands show frequency characteristics of BPF1 and BPF2. The circuit of frequency results for Fig. 14 is composed of lumped-element matching circuits, BPF1 and BPF2 as Fig. 1 (a). Lumped-element matching circuits are set among port 1, BPF1 and BPF2. The circuits of frequency results for Figs. 15 and 16 are composed of a commercial diplexer for Fig. 13 as Fig. 1 (b) and the proposed LPF-HPF diplexer of Fig. 11 as Fig. 1 (c), respectively. Although the passband at the high side of Fig. 16 shifts to higher frequency, it will be matched to the color band of

### Table 5  Comparison with EM Simulation and Measurement for LPF-HPF Diplexer.

|         | EM simulation | Measurement |
|---------|---------------|-------------|
|         | LPF side      | HPF side    | LPF side | HPF side |
| $f_c$ (GHz) | 2.71          | 5.164       | 2.634    | 5.362    |
| $R_L$ (dB)   | 16.87         | 14.25       | 15.06    | 15.37    |
| Maximum     | 1.604         | 1.101       | 1.363    | 1.736    |
| $I_{L}$ (dB) | @2.565 GHz    | @5.35 GHz   | @2.505 GHz | @5.58 GHz |
| $I_{so}$ (dB) | 62.1@8.85 GHz | 45.9@9.955 GHz |         |          |
BPF2 by improving \( f_c \) of the HPF in the LPF-HPF diplexer. The out-of-band rejection characteristics of the high side in Fig. 16 are sharpest compared with Figs. 14 and 15. Figure 17 shows the packaging images for each diplexer. Although the packaging image of our diplexer is bigger than that of other diplexers, that can be downsized when the layouts of the chip elements in the LPF and HPF are re-designed. However, it is careful to configure the layouts of chip elements, input and output (I/O) feed lines and ground patterns since there is a trade-off between the size and the isolation characteristics.

Table 6 shows the \( IL \) and the \( Iso \) characteristics of Figs. 14, 15 and 16. When an LPF-HPF diplexer is set in front of BPFs, the \( Iso \) characteristics are better than in other configurations, while the \( IL \) is slightly higher than others. Although the center frequency and the \( BW \) of the high side is shifted, it can be improved by re-designing the HPF. In this work, it was found that it improving \( Iso \) characteristics between BPFs by setting an LPF-HPF diplexer is effective.

### 3.4 Benchmarking of LPF-HPF Diplexers

Table 7 shows the benchmarking for LPF-HPF diplexers. Most techniques are low temperature co-fired ceramics (LTCC) techniques, so our diplexer is bigger compared to other techniques. However, our diplexer is the smallest.
when compared with Ref., [5] [42] and, [43] which have a planar structure. Moreover, Iso characteristics between lower and higher channels are more than 45 dB.

4. Conclusion

A 2.6-GHz-band LPF and a 5.4-GHz-band HPF were configured using lumped chip elements and patterned lumped elements. The fabricated compact LPF and HPF are in good agreement with configured ones. An LPF-HPF diplexer composed of the configured LPF and HPF has low RL of more than 15 dB, low IL of less than 1.74 dB in the passband and high Iso characteristics of more than 45 dB. In addition, the configured and fabricated diplexer has a compact structure. When BPF-BPF diplexers composed of two BPFs and matching circuits or a commercial diplexer or an LPF-HPF diplexer configured as in Fig. 1 are compared, the LPF-HPF diplexer has higher Iso characteristics of more than 91 dB. Improving Iso characteristics between channels was found to be effective. As benchmarking results, our diplexer is the most compact within a planar structure and has high isolation.

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