1. Introduction

Using high-temperature superconducting materials with critical temperatures around the boiling point of liquid nitrogen (77K), it is possible to construct multi-pole filters with low losses even in the microwave band (high-temperature superconducting filters). Consequently, it is possible to keep the insertion loss in the passband extremely low, yet at the same time achieve both sharp cut-off characteristics at the passband edges and significant attenuation in the stop band. These characteristics lead to improved reception sensitivity and frequency selectivity of receivers in mobile communication base stations, resulting in active R&D of high-temperature superconducting filters in universities, research institutes and corporations inside and outside Japan [1] [2].

We examine microwave band high-temperature superconducting filters, focusing on CoPlanar Waveguide (CPW) configurations. This is because the CPW configuration is advantageous in simplifying the fabrication process and in reducing the depositing cost of superconducting films, since it requires only one side of the substrate to be deposited with superconducting film [3]. Specifically, we assigned quarter-wavelength CPW resonators sequentially on a dielectric substrate with a width of 5.4 mm and a length of 30.5 mm to achieve a performance almost equivalent to the filter design values without pre- and post-tuning. When constructing multi-pole filters of this type, however, we ran into the issue that the dielectric substrate had to be extended by approximately 6.4 mm, which is the length of a resonator, for each extra pole. This article presents the results of designing, constructing and evaluating filters that avoid this increase of substrate area caused by the increased number of pole by assigning the quarter-wavelength CPW resonators in a parallel as well as in interdigital patterns [4] [5].

2. Filter Design and Production

Table 1 shows the filter design specification. The filters are designed by using simulation results both via equivalent circuits and by an electromagnetic simulator [4]. Figure 1 shows the
filter structure and major dimensions and Table 2 shows the principal calculated characteristics of the designed filter, out-of-band attenuation amount and 3-dB bandwidth.

We fabricated the filters using the dielectric substrate and high-temperature superconducting materials shown in Table 1 by means of photolithography\textsuperscript{*1} processing, which corresponds to (1) to (3) and (6) to (8) in the fabrication process shown in Table 3, and ion-milling\textsuperscript{*2} processing, which corresponds to (4) [6]. Photo 1 shows the completed interdigital filter. The external dimensions of the filter are made slightly larger than the space in the waveguide cavity, so that they may be installed more easily in a metal case: 11.6 mm width and 15.4 mm length. The dimensional deviation of the fabricated filter structure from the design dimensions was within 2 µm, which demonstrates that the filter structure developed in this study was fabricated with sufficient processing accuracy.

3. Filter Characteristics and Evaluation

3.1 Measurement Environment

Figure 2 shows a cross-sectional structure of the case used in the filter frequency characteristics measurement. The 0.5 mm thick MgO substrate was placed such that there is 4.5 mm and 3.0 mm of space above and below the substrate, respectively. The case was made from oxygen-free copper and its entire surface was coated with gold. A coplanar microwave probe was used for measurement. The measurements were made upon calibrating at the probe edge and placing the probe directly in contact with the metal pad areas on both edges of the filter.

\*1 Photolithography: A process in which a fine structure is transcribed onto substrate using light whose wavelength is equal to or shorter than that of ultraviolet rays.

\*2 Ion-milling: A processing method in which substrate surface material is removed by ions, generated from gas, accelerated with a strong electric field.

\begin{table}[h]
\centering
\caption{Filter characteristics design results}
\begin{tabular}{|c|c|c|}
\hline
 & Equivalent circuit & Calculated value (electromagnetic field simulator) \\
\hline
Attenuation outside & & \\
passband (dB/10 MHz) & & \\
Lower side & 4.30 & 2.83 \\
Higher side & 3.75 & 4.68 \\
\hline
3-dB bandwidth & & \\
Center frequency (GHz) & 5.004 & 4.996 \\
Bandwidth (MHz) & 207 & 204 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Filter fabrication processes}
\begin{tabular}{|c|}
\hline
Process \\
\hline
(1) Photoresist coating \\
(2) Exposure (transfer circuit patterns) \\
(3) Development \\
(4) Ion-milling \\
(5) Cleaning (peeling off photoresist) \\
(6) Photoresist coating \\
(7) Exposure (transfer circuit patterns) \\
(8) Development \\
(9) Evaporation of electrode materials \\
(10) Lift-off \\
(11) Dicing \\
\hline
\end{tabular}
\end{table}

Lift-off: To peel metal off from areas where photoresist remains by soaking the object in organic solvent.
3.2 Evaluation of Frequency Characteristics

Figure 3 (a) and (b) show the measured frequency characteristics of the fabricated filter at a temperature of 60K, along with the values calculated using the electromagnetic field simulator. Table 4 compares the main characteristics numerically. The electromagnetic field simulator indicated a bandwidth of 204 MHz and a center frequency of 4.996 GHz for the 3-dB band, and the attenuation outside the passband on the low and high frequency sides were calculated to 2.83 dB and 4.68 dB, respectively. For comparison, the measured bandwidth and center frequency were 205 MHz and 5.010 GHz for the 3 dB band, respectively, while the measured attenuation outside the passband on the low and high frequency sides were 2.90 dB and 4.29 dB, respectively; as can be seen, results that agree well with the calculated values could be obtained without any tuning. Since the conductor comprising transmission lines of the filter is assumed to be lossless in the simulation, it is not appropriate to compare the calculated and measured insertion loss directly. Looking only at the measurement data, however, it was found that the average insertion loss in the band was 0.10 dB, a very low loss. Moreover, when estimating the unloaded Q-factor*3 of the individual resonators composing the filter based on the minimum insertion loss of 0.08 dB, high values of over 10,000 were obtained.

Figure 4 shows measurements of the spurious characteristics of the filter, along with the values calculated using the electromagnetic simulator. The measured and calculated values agree well across the entire frequency spectrum measured; the validity of the filter structure and design scheme was thus confirmed. However, undesirable resonances were observed around 10 GHz in the measured and calculated data. This seems to be caused by the half-wavelength resonance of the short-circuited stubs comprising the conductor between adjacent two resonators in Fig. 1. Several resonances were also observed in the frequency band above 13 GHz. These are considered to be caused by the resonant mode of the rectangular waveguide cavity, in other words, the metal case shown in Fig. 2.

Table 4 Various characteristics of filters at temperature of 60K

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Calculated (electromagnetic field simulator)</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-dB bandwidth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center frequency (GHz)</td>
<td>4.996</td>
<td>5.010</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>204</td>
<td>205</td>
</tr>
<tr>
<td>Insertion loss (dB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum value</td>
<td>—</td>
<td>0.08</td>
</tr>
<tr>
<td>Average within passband</td>
<td>—</td>
<td>0.10</td>
</tr>
<tr>
<td>Attenuation outside pass-band (dB/10 MHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower side</td>
<td>2.83</td>
<td>2.90</td>
</tr>
<tr>
<td>Higher side</td>
<td>4.68</td>
<td>4.29</td>
</tr>
</tbody>
</table>

*3 Unloaded Q-factor: A characteristic value for power loss inside a resonator. When this value is high, filters with low insertion loss and high frequency selectivity characteristics can be configured.
3.3 Evaluation of Dependency on Temperature

This section presents the results of evaluating the dependency of the filter insertion loss and center frequency on temperature. It should be noted that we fabricated several filters in this research, and the filter used in this section is different from the one used in previous sections. Figure 5 shows the results of evaluating the relationship between the minimum insertion loss of the filter and temperature. From Fig. 5, it can be seen that the filter’s insertion loss increases as the temperature of the filter increases. This is considered to be caused by increased surface resistance in the high-temperature superconducting film.

Figure 6 shows the evaluation results of relationship between the center frequency of the filter and temperature. From Fig. 6, it can be seen that the center frequency of the filter gradually shifts toward lower frequencies as the temperature of the filter increases. This is considered to be caused by the temperature dependency of both the kinetic inductance \(^4\) of the high-temperature superconducting film and the dielectric constant of the dielectric substrate (MgO).

4. Conclusion

This article presented the results of examination and experimental validation of a configuration method for miniaturized circuits for CPW high-temperature superconducting bandpass filters, which can be used to construct highly efficient receivers for mobile communication base stations. Specifically, we focused on a design scheme for achieving multi-pole filters that do not require a drastic increase in the substrate area by assigning quarter-wavelength CPW resonators in parallel as well as in interdigital patterns, and then fabricated filters in order to experimentally validate the design scheme. We confirmed that the measured and calculated data showed good agreement in the vicinity of the passband as well as in terms of the spurious characteristics. These experimental results confirmed the validity of the interdigital type filter structure as well as the design scheme using a simulation via equivalent circuits and an electromagnetic simulator. Since this filter structure causes little increase in the substrate area, it is highly suited for compact bandpass filters with sharp cut-off characteristics outside the band.

REFERENCES


ABBREVIATIONS

CPW: CoPlanar Waveguide

\(^4\) Kinetic inductance: One of the superconducting inductances and a parameter generated by kinetic energy of superconductive carriers.