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Superconducting Narrowband Filter for Receiver of Weather Radar

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SUMMARY We have developed a high-temperature superconducting (HTS) filter with narrow bandwidth characteristic for receiver of weather radar in order to reduce interference between adjacent radar channels. To realize a filter with which a narrow bandwidth and low insertion loss are compatible, resonators with high unloaded Q (Q_u) value are required. Hairpin microstrip resonators with 1.5 times wavelength were adopted to suppress the radiation loss and achieve a high Q_u value. The developed HTS filter has 8-pole quasi-elliptic function response for sharp skirt characteristic. The measured frequency response of the developed filter shows center frequency of 5370 MHz, insertion loss of 2.04 dB and maximum return loss of 15 dB, which agrees with the designed responses.

key words: *superconducting filter, weather radar, microstrip line*

1. Introduction

Various mobile communication systems have been rapidly adopted in recent years for diverse applications. Consequently, the need for full and effective use of frequency resources is become increasingly acute. The 5250–5850 MHz band is now being used by systems such as those for marine radar and weather radar. Furthermore, as part of efforts to establish a global standard, the 2003 World Radio communication Conference (WRC-03) decided to make additional allotments to wireless access systems, including wireless LAN systems, from a part of this frequency band. Therefore, it is also necessary to consider narrowing the frequency band currently used by weather radar systems and utilizing a higher frequency band for those with a comparatively narrow observation range in order to use this frequency band effectively.

In this paper, we report on the development of narrowband filter technology to reduce the allocated bandwidth of 5 GHz-band weather radar systems, since it is assumed that the 5 GHz band will be expanded for 5 GHz-band wireless LAN systems in accordance with "Guidelines for radio spectrum reallocation" announced by the Ministry of Internal Affairs and Communications of Japan. Since the surface resistance of a high-temperature superconductor (HTS) is two or more orders of magnitude smaller than that of copper even at 5 GHz band, a band-pass filter with a low insertion loss and a narrow bandwidth is expected to be realized by using this characteristic [1]–[3]. And miniaturized HTS band-pass filters for mobile communication systems are developed by using small-sized microstrip spiral resonators on LaAlO$_3$ substrate [16], [17].

In this paper, we have developed a narrow bandwidth HTS filter for the receiver of the radar systems, which has the center frequency of 5730 MHz and the bandwidth of 3 MHz.

2. Filter Design

2.1 Specification

The frequency allocation space between 5 GHz-band weather radar channels is 10 MHz at present. In this paper, we report on the development of the receiving filter, the specification of which is located at 2.5 MHz between adjacent radar channels for effective use of frequency resources. In this case, we suppose the bandwidth of transmission signal at each channel is 1.2 MHz. Figure 1 shows a channel model for 5 GHz-band weather radar systems. In Fig. 1, the n-th channel CH_n shows desired signal. CH_{n-1} and CH_{n+1} show adjacent channels, which are interference spectra. Therefore, it is necessary for the receiving filter to have high-selectivity at center frequency, $f_0 \pm 1.9$ MHz, in order to reduce interference between adjacent channels. According to the specification of the receiving filter, the center frequency is 5370 MHz. The bandwidth of this filter is 3 MHz and the fractional bandwidth is 0.08%. The insertion loss is less than 2.5 dB at f_0. Attenuation at $f_0 \pm 1.9$ MHz is less than -30 dB.

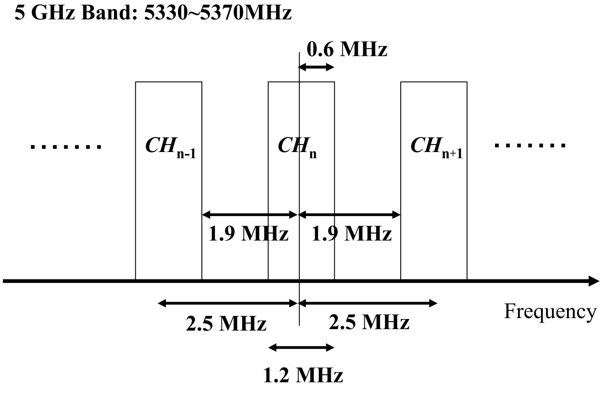

Fig. 1 Channel model for 5 GHz-band weather radar systems.

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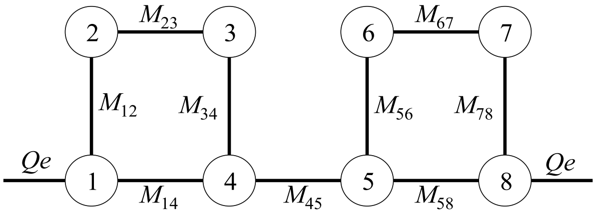


Fig. 2 Coupling structure of 8-pole quasi-elliptic function filter.

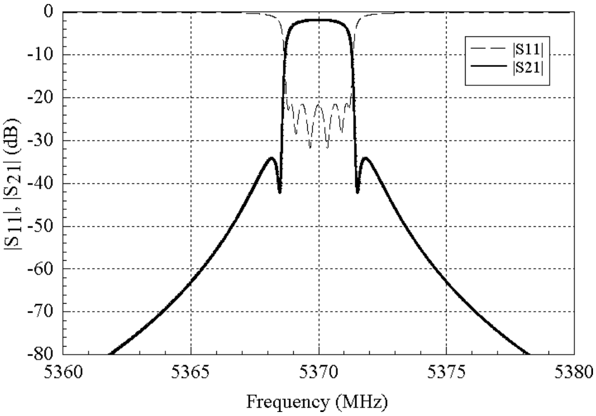


Fig. 3 Calculated transmission response of the 8-pole quasi-elliptic function filter by means of circuit simulation.

2.2 Design of Circuit Structure

In order to realize the sharp-cut filter with the advantage of the high-unloaded Q (Q_u) resonator, the 8-pole quasi-elliptic function structure shown in Fig. 2 was adopted. Numbered circles indicate the resonators. Solid lines indicate the external-QQ_e and coupling factor M. The quasi-elliptic function is realized by coupling between the 1st resonator and the 4th resonator and between the 5th resonator and the 8th resonator [4]. M_{14} and M_{58} couplings for the quasi-elliptic function filter are added in the design theory of the Chebyshev filter [5]. These couplings produce two transmission zeros at both sides of the desired frequency band. Therefore, the quasi-elliptic function filter is able to realize a superior sharp-cut around filter pass-band compared with the Chebyshev filter.

Figure 3 shows a calculated transmission response of the 8-pole quasi-elliptic filter with high Q_u resonator of 40000 by means of a circuit simulation. The filter using the newly developed high Q_u resonator has smaller insertion loss than the filter using the conventional low Q_u resonator. The designed filter has symmetrical coupling structure, the attenuation poles of which are degenerated. The location of attenuation poles is $f_0 \pm 1.9$ MHz. The insertion loss at f_0 is 1.8 dB.

2.3 Design of Resonator

Figure 4 shows an illustration of the loss for microstrip line resonator. The Q_u of microstrip resonator consists of three Q factors, Q for dielectric loss (Q_d), Q for conductor loss (Q_c), and Q for radiation loss (Q_r) [6], [7]. The relationship of Q_u, Q_d, Q_c, and Q_r can be written as

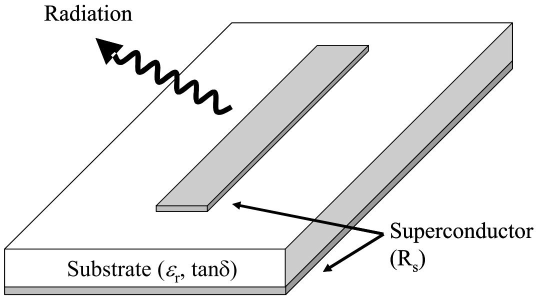


Fig. 4 Illustration of the loss for microstrip line resonator.

Fig. 5 Layout of hairpin microstrip line resonator with 1.5 times wavelength.

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_r}. \tag{1}$$

Q_c decreases at high frequency, since surface resistance of a superconductor is proportional to (frequency)^2 [8], [7]. Q_r decreases by a larger gradient than Q_c. Q_r is smaller than Q_c and is dominant for Q_u in high-frequency region. For this reason, generally, cavity resonators and strip line resonators have been used [9]–[12]. These resonators do not have radiation loss.

The microstrip line resonator radiates from impedance mismatch points, such as end of the line and corner of the line. Generally, the microstrip line resonator with both ends open has radiation loss. In order to suppress the radiation, two radiation points with opposite phase were juxtaposed. Figure 5 shows the layout of hairpin microstrip line resonator with 1.5 times wavelength to suppress the radiation [13]. The w and s indicate the line width and line space respectively. The longer resonator length is, the more Q_u increases, because radiation energy is constant but stored energy increases.

Figure 6 shows the calculated result of Q_u as a function of w and s. The shade of the color indicates Q_u value; black indicates Q_u = 30000, white indicates Q_u = 40000. The radiation loss is suppressed by making w and s small, because it causes the radiation points with opposite phase mutually to be close. On the other hand, the conductor loss is increased by making w and s small, because it causes the current concentration to edge of a microstrip line. For Q_u, the maximum is decided by the trade-off with Q_c and Q_r. As a result, s of 0.5 mm and w of 0.5 mm were determined for a resonator with the maximum Q_u. But the narrowband filter characteristic is more sensitive to unknown

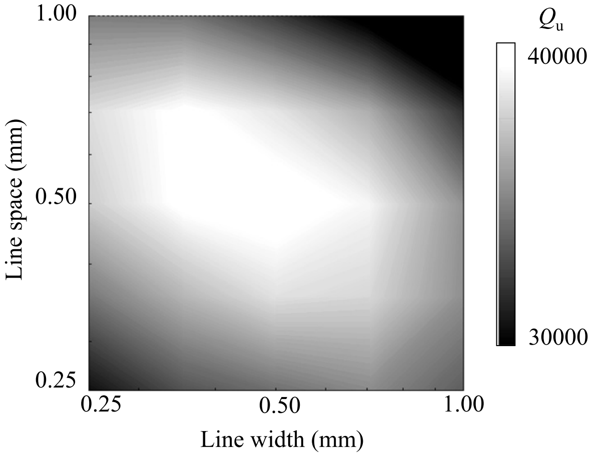


Fig. 6 A calculated result of Q_u as a function of w and s.

Table 1 Comparison of substrates for HTS thin-film devices.

	LaAlO$_3$	MgO	Sapphire
Dielectric permittivity	24	10	anisotropic
Dielectric loss tangent @77K	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-7}$
Thermal conductivity [W/mK] @77K	∼20	120	2000
Cost	high	high	low

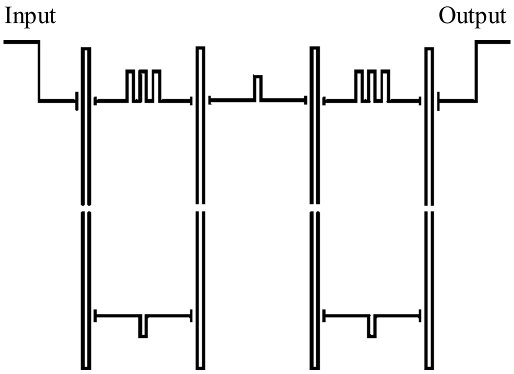


Fig. 7 Layout of a 5 GHz band 8-pole quasi-elliptic function filter.

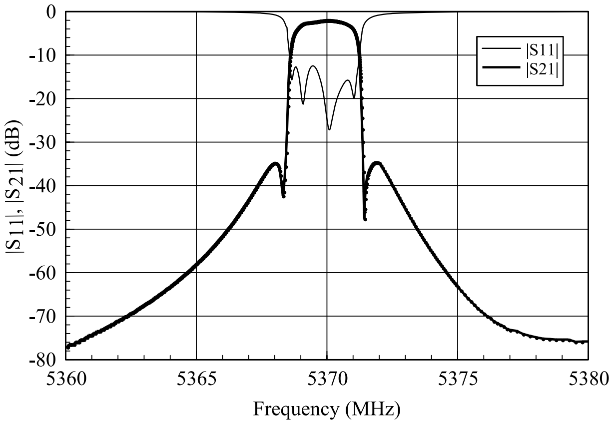


Fig. 8 Frequency response of the 8-pole quasi-elliptic function filter calculated by the moment method.

non-adjacent coupling. Therefore, we used s of 0.35 mm and w of 0.35 mm to reduce radiation.

2.4 Design of Filter

There are three single-crystal substrates that are commonly used for fabrication of HTS thin-film devices. They are lanthanum aluminate (LaAlO$_3$), magnesium oxide (MgO), and sapphire (Al$_2$O$_3$). These substrates are compared in Table 1. Sapphire has several advantages, namely, low dielectric loss, high thermal conductivity at a low temperature, and a lower cost. However, sapphire has the disadvantage of anisotropic dielectric permittivity. HTS filters on r-cut substrate are promising. High-quality YBa$_2$Cu$_3$O$_y$ (YBCO) films grown on r-cut sapphire substrate are routinely obtained. It is difficult to design circuits on sapphire substrate. Dielectric permittivity tensor on the r-cut sapphire substrate can be written as [14]

$$\varepsilon = \begin{pmatrix} 9.4 & 0 & 0 \\ 0 & 10.97 & -0.99 \\ 0 & -0.99 & 10.03 \end{pmatrix} \tag{2}$$

Figure 7 shows the layout of a 5 GHz band 8-pole quasi-elliptic function filter with the high Q_u resonator described above. The filter used the coupling between two adjacent open ends and the coupling using a T-type line between parallel resonators, in turn. The Q_e used a T-type line coupling. The separation between parallel resonators was about 10 mm.

In Fig. 8, frequency response of the 8-pole quasi-elliptic function filter calculated by the moment method (solid line) is shown and compared with the ideal transfer function model (dashed line). From the solid lines, it is seen that the design specifications of the filter are satisfied. The unbalanced transmission zero at the lower side of the passband is caused by cross-couplings among the resonators.

3. Measured Results

3.1 Filter Fabrication

The 8-pole filter, whose design is described above, is fabricated by using HTS YBCO thin films on a sapphire substrate (50 × 56 × 0.35 mm) with a photolithography and dry etching process. The photograph of the filter in a package is shown in Fig. 9.

3.2 Frequency Response

The 8-pole filter is cooled by a small cooler with the dimen-

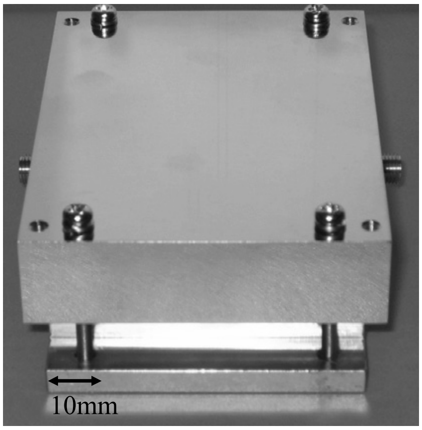
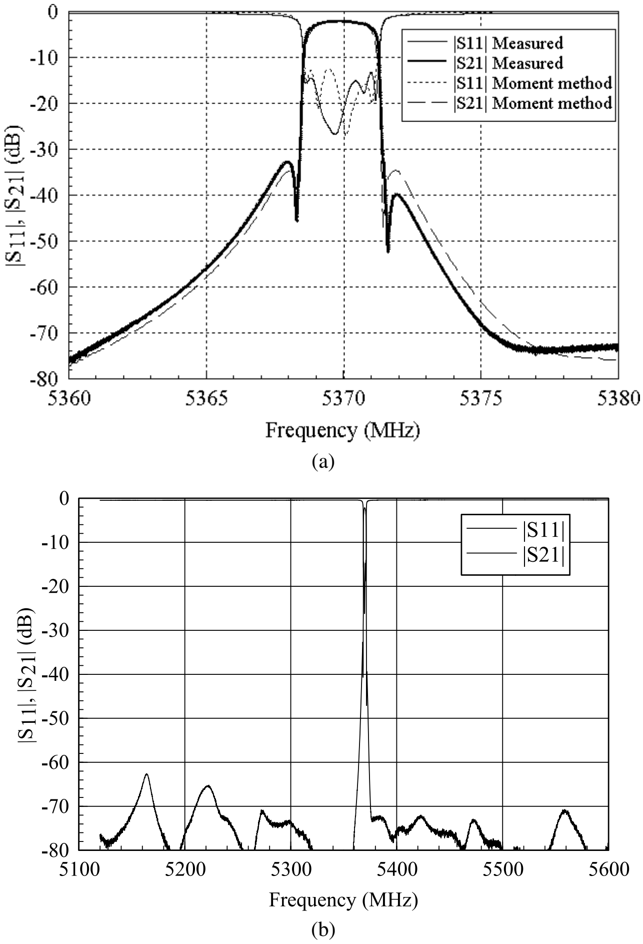


Fig. 9 Photograph of the filter package.



(a)

(b)

Fig. 10 Comparison of simulated and measured frequency response of the 8-pole quasi-elliptic function filter. (a) Narrowband response. (b) Wideband response.

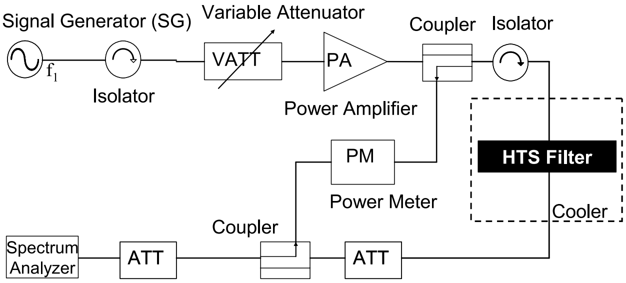


Fig. 11 Schematic diagram of power handling measurement.

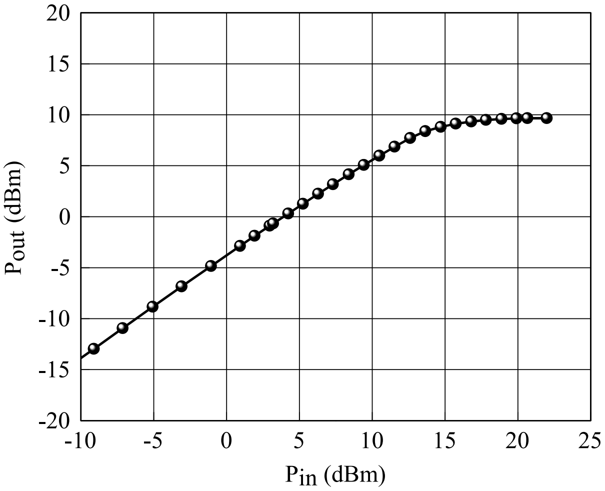


Fig. 12 Measured Input/Output characteristics of the 8-pole filter.

sions of $400 \times 400 \times 250$ mm. The measurement frequency response of the filter is evaluated using a vector network analyzer.

Figure 10 shows the measured frequency response of the 8-pole quasi-elliptic function filter. Figure 10(a) shows narrowband response of the filter with center frequency of 5370 MHz and insertion loss of 2.04 dB including RF cable loss was obtained, which indicated that the Q_u of the hairpin resonator reaches a value of about 40,000. The maximum return loss in the passband is about 15 dB. The attenuation at f_0±1.9 MHz is less than −32.9 dB. Moreover, the transmission zeros were obtained on both sides of desirable band. Although two transmission zeros at both sides of the transmission band are degenerate, the result is in good agreement with that of the circuit simulation and satisfied specifications.

The wideband response of the filter is measured over 5100 to 5600 MHz. As can be seen from Fig. 10(b), the spurious characteristic is suppressed under −60 dB.

3.3 Power Handling Measurement

Power handling capability of the developed filter was measured. Figure 11 shows a schematic diagram of power handling measurement. Input signal is 5370 MHz continuous wave (CW), which is generated at the signal generator (SG). The CW signal is amplified at the power amplifier (PA), the gain of which is 50 dB. Input signal levels are controlled by using variable attenuator. The input and out power of HTS filter is monitored by power meter [15].

Figure 12 shows measured Input/Output characteristics of the developed filter. The power levels entering filter

(P_{in}) varied from −10 to 22 dBm. As a result, power handling capability of the 8-pole receiving filter of over 31 mW (15 dBm) is obtained. The 1 dB compression point is 30 mW (14 dBm). The power handling capability of the HTS filter is limited by critical current density Jc. The current density of hairpin resonator is maximized at the inside corner. In this case, the 8-pole filter is used as the receiver, the power level of which is less than 30 mW. Therefore, the power handling capability of this filter is sufficient for weather radar receiving systems.

4. Conclusion

A narrowband HTS microstrip line filter with a bandwidth of 3 MHz at 5370 MHz on sapphire substrate has been developed. The filter has 8-pole quasi-elliptic function characteristic. A 1.5 times wavelength microstrip hairpin resonator was adopted to suppress the radiation loss. The measured frequency response of the filter using the hairpin resonators shows a low insertion loss, sharp-cut characteristic and sufficient power handling capability, and these results are in good agreement with designed filter response.

Acknowledgments

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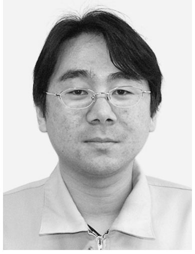

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