A High-Temperature Superconducting Wideband Bandpass Filter at the L Band for Radio Astronomy postprint

Authors: Xinyu Zhu, Jianbin Li, Boyu Lu, Bin Wei, Yifan Jiang, Linan Jiang and Chao Hu

Date: 2023-12-15T00:00:00+00:00

Abstract

To ensure the normal operation of radio astronomy observations, an extremely sensitive receiver system must be installed at the front end of large radio telescopes. An 8-pole wideband high-temperature superconducting (HTS) filter utilizing a coplanar spiral resonator structure with a passband of 1160–1670 MHz has been developed to suppress strong radio frequency interference. The filter is fabricated on a 36 mm × 14 mm YBCO HTS film deposited on a 0.5-mm-thick MgO substrate. The minimum insertion loss measured in the liquid nitrogen temperature region is 0.03 dB, and the first spurious passband appears at 2600 MHz. The measured results are in good agreement with the simulations. The filter can be employed in radio telescope receivers for observations of neutral hydrogen and pulsars, as well as in high-sensitivity satellite navigation instruments.

Full Text

Preamble

Research in Astronomy and Astrophysics, 23:115004 (6pp), 2023 November

https://doi.org/10.1088/1674-4527/acf02f

A High-Temperature Superconducting Wideband Bandpass Filter at the L Band for Radio Astronomy

Xinyu Zhu[12], Jianbin Li[12], Boyu Lu[3], Bin Wei[3], Yifan Jiang[3], Linan Jiang[3], and Chao Hu[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; lijb@bao.ac.cn
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] State Key Laboratory of Low-Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China

Received 2023 May 10; revised 2023 July 6; accepted 2023 July 23; published 2023 October 4

Abstract

To ensure the normal operation of radio astronomy observations, large radio telescopes must be equipped with extremely sensitive receiver systems. We have developed an 8-pole wideband high-temperature superconducting (HTS) filter using a Coplanar Spiral Resonator Structure with a passband of 1160–1670 MHz to suppress strong radio frequency interference. The filter is fabricated on a 36 mm × 14 mm YBCO HTS film deposited on a 0.5 mm thick MgO substrate. The minimum insertion loss measured in the liquid nitrogen temperature region is 0.03 dB, and the first parasitic passband appears at 2600 MHz. The measured results are in good agreement with the simulations. The filter can be used in radio telescope receivers for observing neutral hydrogen and pulsars, as well as in high-sensitivity satellite navigation instruments.

Key words: instrumentation: detectors – techniques: radar astronomy – telescopes

1. Introduction

The L-band is an essential frequency band for satellite navigation, satellite communications, and radio astronomy observations. It covers various active radio services, including the radio satellite navigation and positioning service allocated by the International Telecommunication Union (ITU 2020), the emission spectrum of neutral hydrogen, and the molecular spectrum of hydroxyl groups in radio astronomy. However, strong radio interference from Distance Measuring Equipment (DME) and terrestrial services, such as mobile communication signals on both sides of the band, poses significant challenges. The signals from satellites and astronomical observations are much weaker than the interference, resulting in undesirable nonlinear intermodulation distortion. Furthermore, intermodulation products falling within the useful band cannot be filtered out and will significantly raise the system noise floor, drowning out the desired signal. Therefore, filters are essential components in high-sensitivity receiver systems, and it is necessary to insert a filter before the first-stage low-noise amplifier (LNA) to prevent receiver saturation.

Since the discovery of yttrium-barium-copper-oxygen (Y–Ba–Cu–O) oxide superconductor materials, the superconducting transition temperature has been raised to the liquid nitrogen temperature region (70 K), which is more practical to achieve. The surface resistance of high-temperature superconducting (HTS) film at RF frequencies is 2–3 orders of magnitude lower than that of copper, making losses negligible. Consequently, HTS filters can achieve the extremely low insertion loss, steep skirt slope, and high out-of-band rejection required by high-sensitivity receivers.

Narrowband HTS filters have been extensively used in mobile communications, radar detection, and radio astronomy observations (Zhang et al. 2004, 2005; Zhou et al. 2005). At the beginning of the 21st century, an eight-pole narrowband HTS filter with an insertion loss of 0.3 dB was developed to improve pulsar observations at the Jodrell Bank Observatory (JBO), UK, by suppressing substantial signal interference from TV stations on both sides of the Ultra High Frequency (UHF) band (Zhou et al. 2005).

In recent years, the demand for wideband bandpass filters has also been increasing (Li et al. 2003; Huang 2005; Zhang et al. 2007, 2006). Traditional wideband filter theory requires strong resonator coupling, and coupling coefficients inevitably deviate from design theory when bandwidth exceeds 20%, presenting a significant design challenge. Various design approaches for wideband filters have been proposed to address this problem, including multilayer liquid crystal polymer technology (Hao & Hong 2009), stepped impedance resonator (SIR) structures, parallel-coupled microstrip lines, and defected ground structures (DGS), though these have limitations in fabrication and application. Additionally, various novel resonator configurations have been developed for wideband filters, such as interdigital (IDC) structures (Yu et al. 2009), double-surface capacitor coplanar waveguide (CPW) structures (Xu et al. 2013), and coplanar spiral resonator structures (CSRS) (Shang et al. 2019).

2.1. Resonant Modes Analysis and Structure Design

Refrigeration units carrying filter and low-noise amplifier (LNA) cascade systems are widely applied in large radio telescope receivers to reduce the noise figure (Liu et al. 2021). Filter miniaturization contributes to increased space margins. While using spiral or folded resonators is helpful for miniaturization, the coupling coefficient is not strong enough to construct wideband filters (Ma et al. 2006). The CSRS offers a solution to this limitation. Figure 1 [Figure 1: see original paper] shows the configuration of a resonator pair designed using the CSRS. The electric field is densely distributed on both sides of the transmission line, similar to a CPW structure.

In the CSRS, the grounded stub between adjacent resonators is removed, enabling stronger coupling. The metal strips are bent into a spiral circuit with ends extending to the ground, forming quarter-wavelength resonators. No undesirable resonant modes appear during simulation. Using the full-wave electromagnetic simulation software Sonnet (Sonnet Software 2009), we determined the detailed structure of a single resonator. The resonant frequency decreases with increasing circuit length. For a compact filter operating at low frequencies, we optimized the resonator structure by balancing the number of spiral turns with the width of the entire resonator until the resonant peak equals the filter center frequency (f = fc). One end of the circuit extends to the surrounding ground plane with a length of 1.5 mm, while the other end is adjustable to compensate for frequency offset.

2.2. Structure Layers

Figure 2 [Figure 2: see original paper] illustrates the layers of the CSRS structure. The circuit is etched on an HTS thin film deposited on an MgO substrate. Based on the electromagnetic resonant mode described above, there are two air layers on both sides of the dielectric substrate. H1 represents the height of the air layer above the substrate, and H2 denotes the distance from the substrate to the ground. Simulation results indicate that the thickness of the air layers impacts both resonant frequency and coupling strength. As shown in Figure 3 [Figure 3: see original paper], the frequency increases with increasing values of either height parameter. When H1 is held constant, the growth rate decreases with increasing H2, and vice versa. Furthermore, H2 has a more significant impact on frequency offset than H1, and the growth rates decrease when H2 exceeds 2 mm. The coupling coefficient shows the same tendency.

Considering heat dissipation, overall size, and the relatively weak effect of H2, we selected values of 5 mm and 2 mm for H1 and H2, respectively. The final length h is 2.2 mm. Each resonator is designed with the same linewidth of 0.1 mm for processing and manufacturing convenience. The final dimensions of a single resonator are 2.2 mm × 8.5 mm.

3.1. Resonator Coupling Design

One of the key requirements for designing a wideband filter is achieving strong adjacent coupling (Hong 2011). The coupling coefficient M as a function of the width S between resonators is defined as (1), where f1 and f2 correspond to the lower and upper resonance peak frequencies, respectively. As the first step in our design, the ideal coupling coefficients for filter pairs suitable for Chebyshev polynomials are calculated through simulation software. We then adjust the width S until the simulated value of M equals the ideal value. Considering the requirements of miniaturization and low insertion loss, an 8-pole filter with a return loss greater than 20 dB is derived.

The coupling matrix is represented by mi,j (i = 1, 2, 3, 4, 5, 6, 7; j = i + 1), which denotes adjacent coupling. The external coupling coefficient qe, defined as the coupling strength of the input/output ports to the first resonator, can be determined by (2), where FBW is the fractional bandwidth and Qe denotes the external quality factor, which can be obtained from the center frequency fc and the corresponding group delay $ $0 as (3).

3.2. External Coupling Design

In traditional theory, there are two common structures for external coupling. Open-circuit coupled lines are widely applied in narrowband filters due to their weak coupling strength. The tapped feed line structure proposed in Hong (2011) provides strong coupling that can be employed in this design. The configuration of the external coupling is shown in Figure 4 [Figure 4: see original paper] (only one side illustrated). The input/output feed line is placed at the center of the substrate width for processing and manufacturing convenience. To achieve 50 Ω impedance matching, the length and width of the feed line are selected as 2 mm and 0.48 mm, respectively. The input and output feed lines are directly connected to the end of the first resonator. To strengthen the external coupling and suppress undesirable resonance, an additional grounded stub is implemented in the first resonator. The external coupling can be adjusted by three parameters in this design: the width of the grounded stub W, the length of the vertical feed line to the edge of the ground plane L, and H.

Figure 5 [Figure 5: see original paper] depicts the layout of the complete filter. Every resonator has the same winding direction, meaning adjacent resonator pairs have different coupling modes. Both modes can achieve strong coupling strength reaching up to 0.55 and 0.65, respectively (dashed box in Figure 5). When we combine resonator pairs with the external coupling part, the simulation response is not as expected. We speculate that the extraction of narrowband coupling coefficients based on Chebyshev theory is not suitable for wideband filters. The first optimization step involves narrowing the width of the resonator pair (L12) and tuning the external coupling parameters. H0 is adjusted to compensate for frequency offset.

Eventually, simulation results show excellent performance with 0.03 dB minimum insertion loss and better than −20 dB return loss. The first parasitic passband appears at 2700 MHz, approximately 1.9 times the center frequency.

4. Fabrication and Measurement

The filter is fabricated on a 500 nm thick YBCO thin film deposited on a 0.5 mm thick MgO substrate with a relative dielectric constant of 9.7. After standard photolithography and ion beam etching, the 36 mm × 14 mm filter circuit is formed. We then package it into a metal box to reduce radiation loss. Unlike traditional microstrip line structures, the CSRS substrate does not directly contact the ground. Consequently, we hollow out the bottom of the metal box and preserve a slot to support the substrate, as shown in Figure 2. The input and output feed lines are connected to sub-miniature A (SMA) connectors through gold wire, which is bonded to the circuit feed lines using an Ultrasonic Molecular Bonding Machine.

As shown in Figure 6 [Figure 6: see original paper], the sealed metal box is mounted on a platform inside the Stirling cooler, with an associated computer for temperature adjustment. After setting the cooling temperature to 65 K, the cooling system begins to create a vacuum and cool down, a process that takes approximately one hour. For testing, we selected and calibrated an Agilent N5230C vector network analyzer (VNA). The calibration involves connecting the calibration device to the VNA, with the calibrator's input port (Port A) linked to Port 1 of the VNA and the output port (Port B) connected to Port 2. When the calibrator's red light illuminates, we wait for it to turn green, indicating successful connection. The start and end frequencies are set through the "Freq" button on the dashboard. According to test requirements, the VNA frequency range is set from 300 MHz to 2 GHz.

After pressing the "Cal" button on the VNA, we select E-Cal mode on the screen, choose "2-Port Cal," and initiate calibration. The calibrator can be disconnected after the system completes auto-calibration. Following calibration, we connect the VNA to the reserved ports of the cryogenic cooling platform via transmission line, with input power set at -10 dBm. The S-parameters of the filter can then be read from the screen. No tuning is implemented during measurement.

As depicted in Figure 7 [Figure 7: see original paper], the measured passband ranges from 1160 to 1674 MHz, corresponding to a bandwidth of 36%. The filter exhibits 0.03 dB minimum insertion loss and return loss better than -17 dB. The first spurious passband starts at 2600 MHz, which is lower than the simulation prediction. Figure 8 [Figure 8: see original paper] compares measured and simulated results, showing no obvious offset in the passband of the overall curve. The measured results demonstrate good agreement with simulations.

To test the power stability and temperature variability of the filter, we measured S-parameters under different input power levels and refrigeration temperatures, as shown in Figure 9 [Figure 9: see original paper]. Input power changes have minimal impact on the filter performance (Figure 9 Left). However, as shown in Figure 9 Right, temperature increase causes deterioration of insertion loss and passband deviation. The optimal response is achieved when the temperature drops below 62 K. Table 1 provides a comparison with other reported wideband filters, demonstrating that the CSRS-based filter offers a wider passband and minimal insertion loss.

5. Conclusions

In this paper, a Coplanar Spiral Resonator Structure is applied to design a wideband filter at the L-band for radio astronomy. The filter is fabricated on a 36 mm × 14 mm YBCO HTS film deposited on a 0.5 mm MgO substrate and demonstrates excellent performance at 65 K. The filter offers the advantages of compact configuration and high power handling capacity, making it suitable not only for radio astronomical telescope receivers but also for high-demand satellite navigation communications, radio signal monitoring, and other applications.

Acknowledgments

This work was supported by the Science and Technology Project of Tibet Autonomous Region under grant XZ201901-GB-21, the National Natural Science Foundation of China under grant 11073027, and the Science and Technology Research and Development Program Project of China National Railway Group under grant P2021G011.

References

Hao, Z. C., & Hong, J. S. 2009, IEEE Microw Wirel Compon Lett., 19, 290
Hong, J. 2011, Microstrip Filters for RF/Microwave Applications (2nd ed.; New York: Wiley)
Huang, F. 2005, ITMTT, 53, 2335
ITU 2020, Radio Regulations Articles Edition of 2020
Li, Y., Lancaster, M. J., Huang, F., et al. 2003, IEEE MTTS Int Microw Symp., 1, 551
Liu, H. F., He, C., Wang, J., et al. 2021, RAA, 21, 182
Ma, Z., Kawaguchi, T., Kobayashi, Y., et al. 2006, IEEE MTTS Int Microw Symp., 1, 1197
Shang, S., Wei, B., Cao, B., et al. 2019, ITAS, 29, 1
Sonnet 2009, Sonnet Software (Version 18.25), North Syracuse., https://sonnetsoftware.com
Xu, Z., Wei, B., Cao, B., et al. 2013, IEEE Microw Wirel Compon Lett., 23, 329
Yu, T., Li, C., Li, F., et al. 2009, IEEE Trans Microw Theor Tech., 57, 1783
Zhang, G., Huang, F., & Lancaster, M. J. 2005, IEEE Trans Microw Theor Tech., 53, 947
Zhang, G., Lancaster, M. J., Huang, F., et al. 2004, IEEE MTTS Int Microw Symp., 2, 1117
Zhang, G., Lancaster, M. J., Huang, F., et al. 2006, in European Microwave Conf., 1 (Manchester: IEEE), 661
Zhang, G., Lancaster, M. J., Huang, F., et al. 2007, in European Microwave Conf., 1 (Munich: IEEE), 450
Zhou, J., Lancaster, M. J., Huang, F., et al. 2005, IEEE Trans Appl Supercond, 15, 1004

Note: Figure translations are in progress. See original paper for figures.