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A Novel Compact HTS Interdigital Bandpass Filter Using CPW Quarter-Wavelength Resonators

Zhewang MA[†a)], **Tamio KAWAGUCHI**[†], *Members*, **Yoshio KOBAYASHI**[†], *Fellow*, **Daisuke KOIZUMI**[††],
Kei SATOH[††], *and* **Shoichi NARAHASHI**[††], *Members*

SUMMARY A novel high temperature superconducting interdigital bandpass filter is proposed by using coplanar waveguide quarter-wavelength resonators. The CPW resonators are arranged in parallel, and consequently the filter becomes very compact. The filter is a 5-pole Chebyshev BPF with a midband frequency of 5.0 GHz and an equal-ripple fractional bandwidth of 3.2%. It is fabricated using a YBCO film deposited on an MgO substrate. The measured filtering characteristics agree well with EM simulations and show a low insertion loss in spite of the small size of the filter.

key words: *high temperature superconductor, coplanar waveguide, bandpass filter*

1. Introduction

Recent years have seen rapid applications of various mobile communication systems. As a consequence, full and effective use of frequency resources is strongly demanded than ever been. One prospective approach to address this challenge is to employ low-loss and high-selective filters developed by using high-temperature superconductors (HTS). Compared to microstrip structures, coplanar waveguide (CPW) circuits are expected to offer the advantages of cost-effective chip processing and easy integration with active devices, because CPW structures have HTS films on only one side of their substrates. In [1], a CPW half-wavelength resonator having a high Q-factor was reported, and in [2]–[5], HTS filters using CPW half-wavelength and quarter-wavelength resonators were reported. However, these filters suffered from large insertion losses due to radiation from the bending parts of the filter structures and excess losses caused by the conductor airbridges used to suppress the parasitic CPW modes. In [6], a low-loss 4-pole HTS CPW bandpass filter (BPF) was developed without using airbridges. However, as this filter consists of cascaded quarter-wavelength resonators in a straight line, its size (length) will become very large when a higher degree of filter is wanted. Other CPW filters using quarter-wavelength stepped-impedance resonators were reported in [7] and [8], including Chebyshev and quasi-elliptic BPFs. In [9], the coupling properties of two quarter-wavelength resonators in opposite directions were discussed, but no detailed design of filters was made.

In this paper, a novel HTS CPW interdigital bandpass filter is proposed. First, the variations of the unloaded Q-factor of a CPW quarter-wavelength resonator with its dimensions are investigated, and the results allow us to choose a resonator with a small size and a high Q-factor. Next, the CPW quarter-wavelength resonators are arranged in parallel, but in opposite directions alternately [10]. As a consequence, the interdigital structure of the filter becomes very compact compared with conventional CPW filters mentioned above. No bond-wire airbridges are used in the filter, so losses associated with conductor bridges are avoided, and the low-loss feature of an HTS filter can be fully exploited. A 5-pole Chebyshev BPF is designed based on the theory of direct-coupled resonator filters [11], using an electromagnetic simulator Sonnet em [12]. The filter is fabricated by using a YBCO film deposited on an MgO substrate. The measured frequency response agrees well with the theoretical prediction.

2. Filter Design

The filter to be design is a 5-pole Chebyshev BPF with a midband frequency of 5.0 GHz, a passband ripple of 0.01 dB, and an equal-ripple fractional passband width of 3.2% (160 MHz). The configuration of the 5-pole filter is shown in Fig. 1(a), where CPW quarter-wavelength resonators are arranged in parallel, but their orientations are changed alternatively. The width of the CPW center strip of the input/output lines is 0.22 mm, and the distance between the two side grounds is 0.40 mm, so that the characteristic impedance Z_0 is 50 Ω. The length L of the resonators is approximately one quarter-wavelength of the CPW dominant mode. The equivalent circuit of the filter is given in Fig. 1(b), where the external Q-factors and the coupling coefficients $k_{i,i+1}$ (i=1, 2, 3, 4) are calculated by using the well-known formulas in [11], together with the specifications of the filter. We have $Q_{e1} = Q_{e2} = 23.92$, $k_{12} = k_{45} = 3.17 \times 10^{-2}$, and $k_{23} = k_{34} = 2.18 \times 10^{-2}$.

The filter is shielded by a copper box with cross sectional dimensions 11.0 mm × 8.0 mm, as is shown in Fig. 2(a). The distance between the CPW YBCO film and the top of the package is 4.5 mm, and is 3.0 mm between the MgO substrate and the bottom of the package. The dimensions of the shielding box are chosen to avoid package resonance in the frequency range of our interest. The MgO

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[†] The authors are with the Department of Electrical and Electronic Systems, Saitama University, Saitama-shi, 338-8570 Japan.

[††] The authors are with NTT DoCoMo, Inc., Wireless Laboratories, Yokosuka-shi, 239-8536 Japan.

a) E-mail: ma@ees.saitama-u.ac.jp

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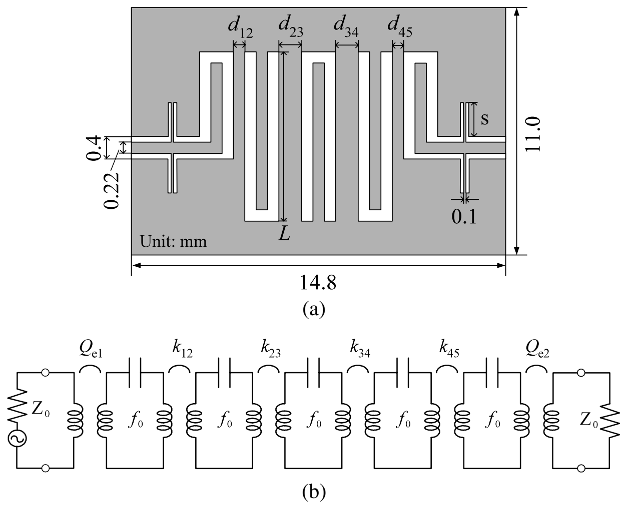
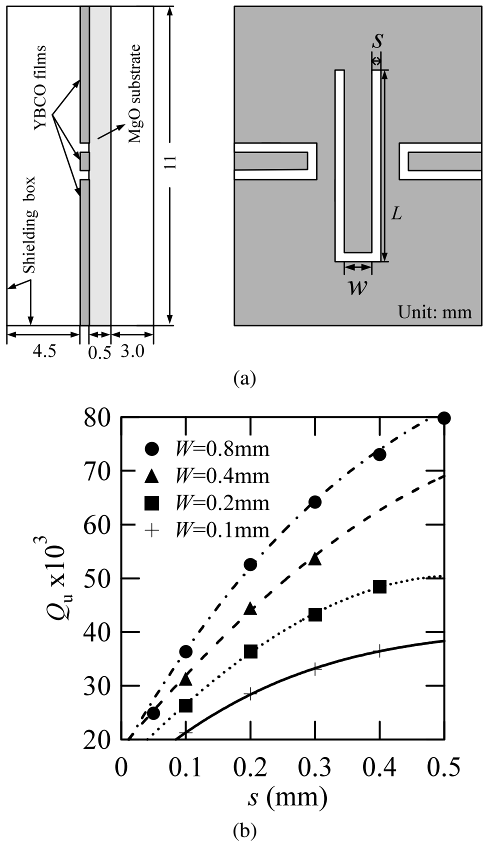


(a)

(b)

Fig. 1 (a) Configuration of a 5-pole interdigital BPF using CPW quater-wavelength resonators, and (b) its equivalent circuit.



(a)

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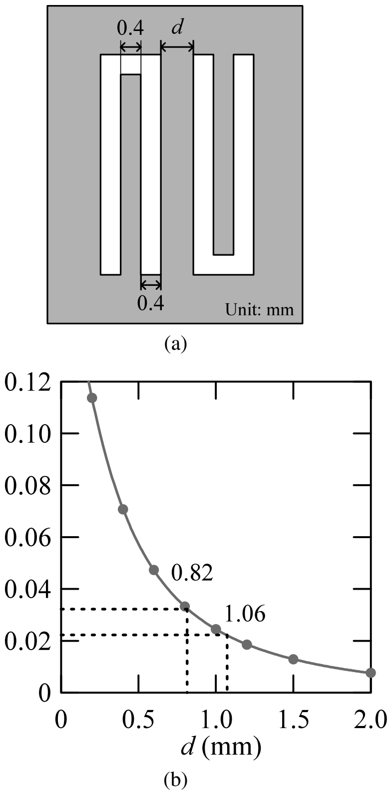
Fig. 2 (a) Configuration of a shielded CPW quater-wavelength resonator, and (b) variation of Q_u with the strip width w and slot width s of the resonator.

substrate has a dielectric constant of ε_r=9.68 at 70 K and a thickness of 0.5 mm. The thickness of the YBCO is 0.5 μm, but is ignored in the filter design.

In order to get a high-Q resonator and then realize a filter with better performance, we investigated first the variations of the unloaded Q-factor, Q_u, of the CPW quarter-wavelength resonator with the strip width w and slot width s of the resonator, as shown in Fig. 2(a). We use Sonnet em to compute Q_d due to the dielectric loss of the MgO substrate, Q_b due to the surface resistance R_s of the top and bottom copper plates of the shielding box, and Q_y due to the surface resistance R_{sYBCO} of the CPW YBCO films, separately, and get finally the unloaded Q-factor, Q_u, of the resonator. In the computation, the resonator has a length of L = 6.45 mm and resonates at 5 GHz, the loss tangent of the MgO substrate is 2.3×10^{-7}, R_s = 7.6 mΩ, and R_{sYBCO} = 0.04 mΩ. These values are estimated at 70 K and 5 GHz based on our measurements of the MgO substrates, YBCO films, as well as copper plates. The influence of the side copper walls of the shielding box are ignored because first they are far away from the resonator strip, and second they are defined as unchangeable perfect conductors by the simulator.



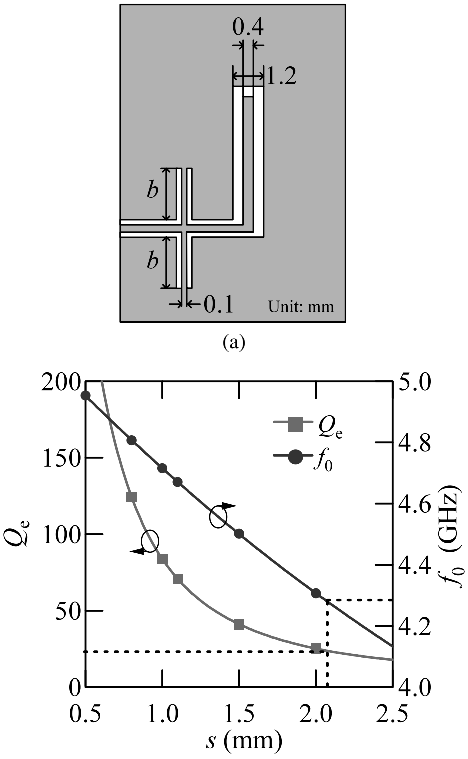
(a)

(b)

Fig. 3 (a) Coupled CPW quarter-wavelength resonators, and (b) variation of coupling coefficient k versus distance d.

Figure 2(b) shows the computed Q_u with the strip width w and slot width s of the resonator. While w is varied from 0.1 to 0.8 mm, s is varied from 0.05 to 0.5 mm. It is seen that by choosing larger values of w and s, we can get larger values of Q_u. A compromise between small size and high-Q of the resonator is determined, and we select w=0.4 mm and s=0.4 mm for the resonator which, as seen from Fig. 2(b), owns a Q_u of about 60,000.

Figure 3(a) illustrates two coupled CPW interdigital quarter-wavelength resonators. The coupling coefficient k is computed and its variation versus the distance d between two resonators is shown in Fig. 3(b). We get d_{12} =



(a)

(b)

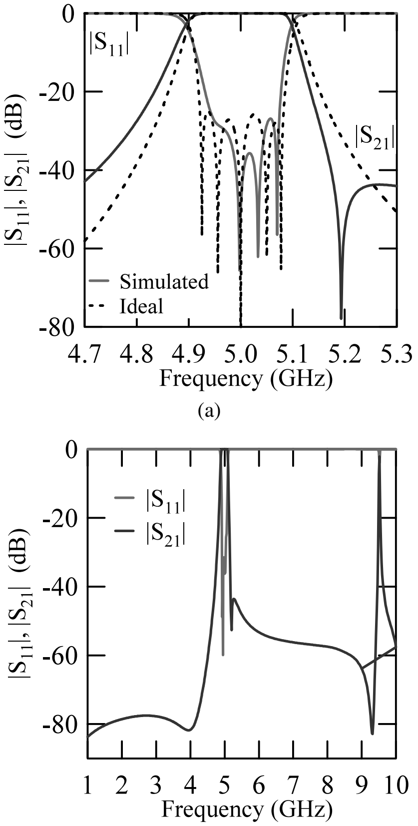
Fig. 4 (a) Feeding structure of the filter using short-circuited stubs, and (b) variation of Q_e and f_0 versus the length b of the short-circuited stubs.

d_{45}=0.82 mm and d_{23} = d_{34}=1.06 mm to obtain the required k values of the filter.

The external coupling between the resonator and the input/output feed line is controlled by changing the length b of the short-circuit stubs shown in Fig. 4(a). The variation of external Q_e and resonant frequency f_0 of the resonator versus b is depicted in Fig. 4(b). We get b=2.09 mm to realize the required Q_e value. Because of the coupling with external circuits, the resonant frequencies of the 1st and 5th resonators in Fig. 1(a) decreased to about 4.28 GHz, as indicated by Fig. 4(b). To compensate for this frequency reduction, the lengths of the 1st and 5th resonators are reduced.

Figure 5(a) shows frequency responses of the designed filter. The solid curves are simulated from Fig. 1(a) using Sonnet em, and the broken lines are calculated from the equivalent circuit shown in Fig. 1(b). From the solid lines, it is seen that the design specifications of the filter are satisfied. The transmission zero at the upper side of the passband is caused by cross-couplings among the resonators.

The wideband frequency response of the filter computed by Sonnet em is shown in Fig. 5(b). It is seen that the first spurious resonance appears at about 9.4 GHz. Current distributions around the resonators indicate that this spurious resonance may be considered as caused by the half-wavelength resonance of the short-circuited stubs between two CPW quarter-wavelength resonators in Fig. 1(a). Another reasonable explanation of this spurious resonance is that, if the filter resonators are considered as half-wavelength slot-mode resonators that are folded into U-shapes, the first spurious resonance of the filter is then the one-wavelength resonance of the slot-mode resonators. Actually, other spurious resonances are also observed at about 10.3 GHz, 12.7 GHz, and frequencies around 15 GHz. These spurious resonances may be caused the slot-modes, the above-mentioned short-circuited stubs, and even resonances of the shielding box. Discrimination of these spurious resonances is not an easy task, but needs careful investigations, including computation and analysis of the EM fields and current distributions around the resonators at different frequencies of the spurious resonances. Some related discussions can be found in [13] and [14].



(a)

(b)

Fig. 5 (a) Simulated narrowband frequency response of the 5-pole BPF using CPW quarter-wavelength resonators, and (b) the simulated wideband response.

3. Filter Measurement

The filter designed above is fabricated by using a photolithography and dry etching process. Without any pre- and post-tuning, the filter is measured by using a pair of coplanar microprobes and a network analyzer. The frequency responses of the filter measured at 60 K are shown in Fig. 6 by solid lines, and they agree well with the EM simulated results depicted in broken lines. The measured results show a midband frequency of 5.01 GHz, and a passband width of 154 MHz. The minimum passband insertion

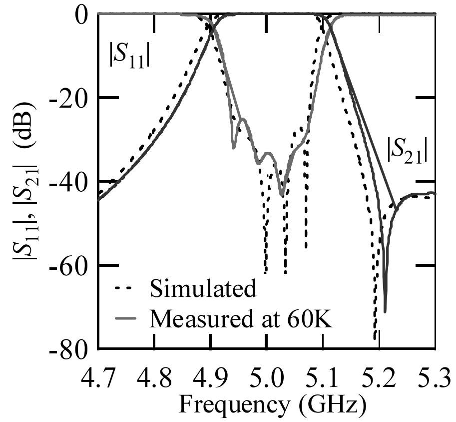


Fig. 6 Comparison of the measured and simulated frequency responses of the filter. The measurement is made at 60 K.

loss is about 0.08 dB, and this indicates that the unloaded Q_u of the CPW quarter-wavelength resonators reaches a value larger than 10,000. The maximum reflection loss in the passband is lower than 20 dB. The measured midband frequency (5.01 GHz) is about 10 MHz higher than the designed 5.0 GHz. The reason is probably that the actual dielectric constant of the MgO substrate is a little bit smaller than the given nominal value, ε_r=9.68 at 70 K.

4. Conclusion

A novel compact HTS interdigital bandpass filter with no airbridges is proposed by using CPW quarter-wavelength resonators. The 5-pole Chebyshev bandpass filter is designed, fabricated, and measured. The measured frequency response agrees reasonably with our theoretical prediction, and shows a low insertion loss in its passband.

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Zhewang Ma was born in Anhui, China, on July 7, 1964. He received the B.Eng. and M.Eng. degrees from the University of Science and Technology of China (USTC), Hefei, China, in 1986 and 1989, respectively. In 1995, he was granted the Dr. Eng. degree from the University of Electro-Communications, Tokyo, Japan. He was a Research Assistant in 1996, in the Department of Electronic Engineering, the University of Electro-Communications, and became an Associate Professor there in 1997. Since 1998, he has been an Associate Professor in the Department of Electrical and Electronic Systems, Saitama University, Japan. From 1985 to 1989, he was engaged in research works on dielectric waveguides, resonators and leaky-wave antennas. From 1990 to 1997, he did studies on computational electromagnetics, analytical and numerical modeling of various microwave and millimeter wave transmission lines and circuits. His current research works are mainly on microwave and millimeter wave filters, measurements of dielectric materials and high temperature superconductors. He received Japanese Government (Ministry of Education, Culture, Sports, Science and Technology) Graduate Scholarship from 1991 to 1993. He was granted the URSI Young Scientist Award in 1993. From 1994 to 1996, he was a Research Fellow of the Japan Society for the Promotion of Science (JSPS). Dr. Ma is a member of IEEE. He has served on the Editorial Board of *IEEE Transactions on Microwave Theory and Techniques*, Review Board of *IEEE Microwave and Wireless Components Letters*, and Review Board of *IEICE Transactions on Electronics*, Japan. He is a member of the Steering Committee for 2002 and 2006 Asia Pacific Microwave Conference (APMC2002).

Tamio Kawaguchi was born in Ibaraki, Japan, in 1980. He received B.E. degree in electrical engineering from Saitama University, Japan, in 2003, and is currently pursuing his M.E. degree at the same university. He is engaged in the design of microwave planar filters.

Yoshio Kobayashi was born in Japan on July 4, 1939. He received the B.E., M.E., and D.Eng. Degrees in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan, in 1963, 1965, and 1982, respectively. Since 1965, he has been with Saitama University, Saitama, Japan. He is now a professor at the same university. His current research interests are in dielectric resonators and filters, measurements of low-loss dielectric and high-temperature superconductive (HTS) materials, and HTS filters, in microwave and millimeter wave region. He served as the Chair of the Technical Group on Microwaves, IEICE, from 1993 to1994, as the Chair of the Technical Group of Microwave Simulators, IEICE, from 1995 to1997, as the Chair of Technical Committee on Millimeter-wave Communications and Sensing, IEE Japan, from 1993 to1995, as the Chair of Steering Committee, 1998 Asia Pacific Microwave Conference (APMC'98) held in Yokohama, as the Chair of the National Committee of APMC, IEICE from 1999 to 2000, and as the Chair of the IEEE MTT-S Tokyo Chapter from 1995 to1996. He also serves as a member of the National Committee of IEC TC49 since 1991, the Chair of the National Committee of IEC TC49 WG10 since 1999 and a member of the National Committee of IEC TC90 WG8 since 1997. Prof. Kobayashi received the Inoue Harushige Award on "Dielectric filters for mobile communication base stations" in 1995. He is a Fellow of IEEE and a member of IEE Japan.

Daisuke Koizumi received B.E. and M.E. degrees in electrical and communication engineering from Tohoku University, Sendai, Japan, in 1999 and 2001, respectively. He joined NTT DoCoMo, Inc. in 2001, where he engaged in research on microwave circuit technologies. He is currently developing high-performance planar filters.

Kei Satoh received the B.E. and M.E. degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1990 and 1994, respectively. He joined NTT Tohoku Mobile Communications Network Inc. in 1994. He is currently a Research Engineer of Wireless Laboratories at NTT DoCoMo, Inc. His current research interest includes high-performance planer filters for cellular systems.

Shoichi Narahashi received the B.E. degree in electrical engineering, and the M.E. degree in electronic engineering, from Kumamoto University, Kumamoto, Japan, in 1986 and 1988, respectively. From 1988 to 1992, he was with the Nippon Telegraph and Telephone (NTT) Radio Communications Systems Laboratories, where he was engaged in research on base station equipment for cellular radio systems. Since 1992, he has been with the NTT DoCoMo, Inc., where he is currently an Executive Senior Research Engineer, Director. He is now doing researches on microwave circuit technologies including superconducting devices, power amplifiers and MEMS technologies for mobile radio systems. He is a member of IEEE and the Society of Instrument and Control Engineers.