Novel dual mode disk-shaped resonator filter with HTS thin film

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Abstract. We propose a novel dual mode disk-shaped resonator filter with high temperature superconductor (HTS) thin films. The 5 GHz-band YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) microstrip dual mode disk resonator filter on an MgO (100) substrate keeps a perfect circle shape and a waveguide line of about a half-wavelength that is capacitively-coupled with the disk resonator to generate a dual mode. The fabricated filter had an equivalent frequency response of a two-pole filter with two attenuation poles. The coupled coefficient of two orthogonal modes can be controlled by the length of coupled waveguide line and the gap space between feeder and disk resonator. The fabricated filter showed very low third-order intermodulation distortion (IMD3) of -73 dBc with an output power of 10 W at a temperature of 65 K. In addition, the proposed structure can be fabricated using a side lithography and etching processes. This is an advantage for multi-stage filter applications. We believe this filter is a promising candidate structure for RF transmit system applications.

1. Introduction

In future wireless communications, it will be important to use radio-waves effectively because the optimum frequency band is limited for each application. A solution is suppression of spurious signals employing a high Q filter of high temperature superconductor (HTS) thin films on a low loss substrate. This is because HTS surface resistance at microwave frequencies is lower than normal metals, such as Gold and Copper. For transmit system applications of the base stations, filters with high power handling and low intermodulation distortion (IMD) are required [1]. Many kinds of HTS planar-circuit filters have already been studied [2], of which a disk shaped microstrip resonators with HTS film on MgO substrate [3-6] has been found to have high power handling and IMD performance. On the other hand, the diameter of a disk shaped resonator filter is half a wavelength ($\lambda$) or integral multiple of it. As it consumes a large space compared to other patterned filters, a disk shaped filter with dual mode is desired from the point of view saving device space. In addition, an effective RF filter has attenuation poles to obtain high filter performance [2].

A disk resonator with a disk-like pattern and a small notch is a well known dual-mode structure [2, 7]. However, the current concentration at the notch is higher than in other parts of the resonator. It is one of the limiting factors of the input power in the notched HTS disk resonators. Also, the current concentration in the film leads to nonlinear behaviour of a HTS thin film [8]. To improve IMD performance, it is necessary to reduce nonlinear behaviour [9]. This is expected to equalize the current.
distribution in the resonator improving high power handling and IMD performance. Therefore, the shape of the resonator disk should be kept smooth. Various kinds of methods to generate a dual mode with smooth shape have already been proposed [10, 12]. There were reports [10, 11] of the dual mode filter which has an upper conducting layer and a dielectric substrate on microstrip disk resonators. Additionally, an elliptic-disk dual mode filter [12] was studied. These filters have high power handling capability as compared to notched filters.

In this paper, we propose a dual mode disk-shaped microstrip resonator with a coupled waveguide line. The disk resonator keeps a perfect circle shape and a waveguide line of about half a wavelength is capacitively-coupled with a disk resonator to generate a dual mode.

In addition, it can be fabricated using only a one side patterning process. This is an advantage for multi-disk filter fabrication. A 5 GHz-band YBCO microstrip dual mode disk resonator filter with a coupled waveguide line was demonstrated and the power handling and IMD performance were discussed.

2. Analysis of dual mode disk-shaped resonator filter with a coupled waveguide line

Figure 1 shows a schematic circuit pattern view of the proposed dual-mode disk-shaped microstrip resonator with a coupled waveguide line. The input and output feeders are orthogonally capacitively-coupled with the disk resonator. To generate a dual mode, a coupled waveguide line of about $\lambda/2$ of equivalent electrical length is capacitively-coupled. We considered that two orthogonal modes, horizontal and vertical, were coupled through a coupled waveguide line. In addition, these parts are located on the same layer. The device with two-pole band pass filter (BPF) can be expected to have dual mode resonance.

This filter structure was analyzed using an electromagnetic (EM) simulator using the moment method. In the simulation conditions, MgO (100) with $\varepsilon_r = 9.7$, $\delta = 5 \times 10^{-6}$ and thickness 0.5 mm was used for the substrate. HTS thin films, for signal and ground layers, and a package material for the shield, were assumed to be perfect conductors. The package inner size used was for 20 mm square.

![Figure 1. Schematic view of dual mode disk-shaped resonator filter with a coupled waveguide line](image)

To design the S parameter frequency responses of the device, we assumed that the coupling coefficient ($k$) of two orthogonal modes is related to the delay length of the coupled waveguide. The delay length can be controlled by the length and capacitance between feeder and disk resonator. The coupling coefficient as a function of the length of coupled waveguide was analyzed using simulation. The coupling coefficient is described by [13]

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$

(1)
Where, \( f_1 \) and \( f_2 \) are the lower and higher resonant frequencies of orthogonal modes, respectively. If the coupling coefficient is changed by delay length, it is expected that the delay is also changed by the gap between feeder and disk resonator. The delay length as a function of the gap between feeder and disk resonator was analyzed. A notched filter with the same band width was simulated to compare with the current density.

3. Experimental
An MgO (100) substrate with thickness 0.5 mm and with epitaxial YBa\(_2\)Cu\(_3\)O\(_{7-x}\) (YBCO) thin films deposited both sides were used. Each YBCO film thickness was 500 nm. One side of the YBCO thin film was patterned using photolithography [14]. The 5 GHz dual-mode disk resonator BPF was designed and fabricated. The band width of filter was 100 MHz at -3 dB down. The diameter of the disk resonator was 11 mm. The filter circuit was packaged in a gold-plated copper box.

The frequency response of S parameters was measured at a temperature of 65 K with a network analyzer. The nonlinear performance was measured using a two-tone method. Two power sources combined near the lower and higher cut-off frequency (fundamental) and increased by 10 kHz were inputted into filter. The output power of the fundamental and third-order intermodulation distortion (IMD3) was measured using a spectrum analyzer with an input power of up to 10 W at 65 K.

4. Results and discussion
Figure 2 shows simulated frequency responses of dual mode disk-shaped resonator filters with a coupled waveguide line as a function of the coupled waveguide line length. This filter has the equivalent frequency response of a two-pole filter with two attenuation poles. Therefore, it is believed that the waveguide line of \( \lambda/2 \) only affects the delay line. It shows that the coupling coefficient of two orthogonal modes is changed with the delay length of coupled waveguide.

![Figure 2](image)

**Figure 2.** Calculated frequency response of dual mode disk-shaped resonator filter with a coupled waveguide line.

Figure 3 shows the calculated coupling coefficient as a function of the coupled waveguide line length, using the simulation results. The length of the waveguide line included the feeder length. The line length was normalized by the wavelength. This means that the coupling coefficient of the filter can be controlled by the length of the coupled waveguide line. If the coupling coefficient can be changed by the phase delay, the electrical delay at gaps between the feeder and the disk resonator also influences it. The electrical delay was calculated using a disk resonator with the opposed feeder. Figure 4 shows the
delay wavelength at TM\textsubscript{11} resonance around 5 GHz as a function of gap space from 25 \(\mu\)m to 75 \(\mu\)m. This data show differences of the delay wavelength from a 75 \(\mu\)m gap space. The phase delay is increased due to the narrow gap space.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure3}
\caption{Calculated coupling coefficient (k) as a function of coupled waveguide line length.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure4}
\caption{Calculated delay wavelength as a function of gap space.}
\end{figure}

Based on the above results, the 5 GHz-band dual mode filter was designed and fabricated. The external Q (Qe) of the filter was also optimized with the feeder width and the gap between feeder and resonator (not shown). Figure 5 shows a photograph of the fabricated filter packaged in a shield case without a shield cover. Figure 6 shows the measured frequency response of the fabricated filter at a temperature of 65 K. Fabricated filter has two-pole filter performance with two attenuation poles and reflection loss below 20 dB at the passband frequency.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure5}
\caption{A photograph of the fabricated filter without a shield cover. The HTS filter was packaged in a shield case.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure6}
\caption{Measured frequency response of the fabricated resonator filter at a temperature of 65 K.}
\end{figure}

Figure 7 shows output power of fundamental and IMD3 as a function of input power for the filter sample at a temperature of 65 K. Figure 7 (a) and (b) shows different input frequency of lower and higher edges of the bandwidth, respectively. IMD3 performance of -73 dBc at output power of 10 W was obtained at the lower edge of the bandwidth. At the higher edge of the bandwidth, the output power of IMD3 is very low, about the same as the measurement system noise level. The current
concentration was analyzed using an EM simulator. The coupled waveguide line is about \( \lambda/2 \), but does not perform as a resonator. There is no significant resonance point in the coupled waveguide at the band pass frequency region. However, the current density at bend points of the coupled line near the feeder is higher than at other points. But the simulated current density is two times as smaller as it at the notch of a notched HTS disk resonator with same bandwidth. If it can be reduced, the filter is expected to have high IMD performance. Future analysis should consider the reduction of current density in these regions.

![Graphs showing output power of fundamental and IMD3 as a function of input power for the filter sample at temperature of 65 K.](image)

**Figure 7.** Output power of fundamental and IMD3 as a function of input power for the filter sample at temperature of 65 K.

5. Conclusion

A novel dual mode disk-shaped microstrip resonator filter with a coupled waveguide line employed YBCO thin film was demonstrated. The fabricated filter of 5 GHz-band with 100 MHz bandwidth has equivalent frequency response of a two-pole filter with two attenuation poles. The coupled coefficient of two orthogonal modes can be controlled by the length of the coupled waveguide line and the gap space between the feeder and the disk resonator. This filter has a very low IMD3 of -73 dBc with an output power of 10W obtained at a temperature of 65 K. We believe the presented resonator with HTS films is a candidate element structures for multi-stage BPFs with higher cut-off frequency responses in transmit system applications.

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7. References

[1] Nobuo Nakajima, and Toshio Nojima 2002 *IEICE Trans. Electron.* **E85-C** 1950

[2] Jia-Sheng Hong and M.J. Lancaster 2001 *Microstrip Filters for RF/Microwave Applications* John Wiely & Sons, Inc., New York
[3] T. Dahm, D. J. Scalapino, and Balam A. Willemesen 1999 *J. Appl. Phys.* **86** 4055
[4] Alan P. Jenkins, Kedaar S. Kale, David J. Edwards, and David Dew-Hughes 1997 *IEEE Trans. Appl. Supercond.* **7** 2793
[5] H. Higashino, A. Enokihara, and K. Setsune 1996 in *Advances in Superconductivity IX (ISS’96)* 1239
[6] Kazunori Yamanaka, Akihiko Akasegawa, Manabu Kai, and Teru Nakanishi, 2005 *IEEE Trans. Appl. Supercond.* **15** 1024
[7] H.A. Wheeler 1965 *IEEE Trans. MTT-13* 172
[8] Sang Yeol Lee; Kwang Yong Kang; Dal Ahn 1995 *IEEE trans. Appl. Supercond.* **5** 2563
[9] D. E. Oates, S.-H Park, D. Agassi, G. Koren, and K. Irgmaire 2005 *IEEE trans. Appl. Supercond.* **15** 3589
[10] A. Akasegawa, K. Yamanaka, T. Nakanishi, and M. Kai 2006 *Physica C*, **445-448** 990
[11] K. Yamanaka, A. Akasegawa, M. Kai and T. Nakanishi 2006 *Physica C*, **445-448** 998
[12] Kentaro Setsune and Akira Enokihara 2000 *IEEE trans. Microwave Theory and Techniques* **48** 1256
[13] G.L. Mattheai, L. Young, and E.M.T. Jones 1964 *Microwave-filters, Impedance-Matching Networks, and Coupling Structures*, McGraw-Hill, New York
[14] K. Yamanaka, A. Akasegawa, M. Kai, and T. Nakanishi 2005 *IEEE Trans. Appl. Supercond.* **15** 1024