Low-Loss Bandpass Filter Using Dielectric Rod Resonators Oriented Axially in a High-T_c Superconductor Cylinder

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ABSTRACT

A maximally flat type bandpass filter using two $TM_{01\delta}$-mode dielectric rod resonators oriented axially in a high-Tc superconductor cylinder is designed with 3dB bandwidth 36MHz at 11.958GHz. For this filter the insertion loss below 0.1dB and the frequency temperature coefficient of -2.7ppm/K are realized in the range 20 to 50K.

I. INTRODUCTION

Recent development in high-T_c superconductor materials enables us to realize low-loss microwave devices[1]-[4]. This paper discusses design and characteristics of a bandpass filter using two $TM_{01\delta}$-mode dielectric rod resonators oriented axially in a high-T_c superconductor cylinder. In order to eliminate the need for filter adjustment at low temperature range after the filter is adjusted finely at room temperature, a precise design of the resonator is performed to realize high temperature stability of resonant frequency. A single resonator which contains a low-loss $Ba(MgTa)O_3$ ceramic rod and a $YBa_2Cu_3O_y$ bulk cylinder realizes very high unloaded Q(Q_u) value of 150,000 at 12GHz and excellent temperature stability of 1.7 ppm/K in the temperature range 20 to 300K. A maximally flat type bandpass filter is fabricated by using these two resonators and is designed with 3dB bandwidth 36MHz at a center frequency 11.958GHz for channel 13 of satellite broadcasting in Japan. This filter has low insertion loss below 0.1dB and excellent temperature stability of -2.7ppm/K in the range 20 to 50K.

II. RESONATOR DESIGN

Fig. 1 shows configuration of a $TM_{01\delta}$-mode dielectric rod resonator. A dielectric rod resonator having diameter D, length L, relative permittivity ε_r, and loss tangent $\tan\delta$ is supported with a resonator support ring in a conductor cylinder having diameter d and conductivity σ. The temperature coefficient of the resonant frequency f_0, τ_f is given by

$$\tau_f = A_r\,\tau_r + (A_D+A_L)\,\tau_\alpha + A_2\,\tau_2 + A_d\,\tau_c \qquad (1)$$

where the temperature coefficient of ε_r, τ_r, the linear expansion coefficient of the rod τ_α, the temperature coefficient of ε_2, τ_2, and the linear expansion coefficient of the cylinder τ_c are defined by

$$\tau_r = \frac{\Delta\varepsilon_r}{\varepsilon_r \Delta T},\quad \tau_\alpha = \frac{\Delta D}{D\Delta T} = \frac{\Delta L}{L\Delta T},\quad \tau_2 = \frac{\Delta\varepsilon_2}{\varepsilon_2\Delta T},\quad \tau_c = \frac{\Delta d}{d\Delta T} \qquad (2)$$

and also the numerical constants of these coefficients are calculated from

$$A_r = \frac{\varepsilon_r}{f_0}\frac{\partial f_0}{\partial \varepsilon_r},\quad A_D = \frac{D}{f_0}\frac{\partial f_0}{\partial D},\quad A_L = \frac{L}{f_0}\frac{\partial f_0}{\partial L},$$
$$A_2 = \frac{\varepsilon_2}{f_0}\frac{\partial f_0}{\partial \varepsilon_2},\quad A_d = \frac{d}{f_0}\frac{\partial f_0}{\partial d} \qquad (3)$$

In the above f_0 and its differentiations can be calculated numerically from the characteristic equation analyzed rigorously by the mode-matching technique[5].

The resonator used for filter construction contains a low-loss BMT ceramic rod of $\varepsilon_r = 24$, a foamed polystyrene support of $\varepsilon_2 = 1.03$ and a YBCO bulk cylinder. For the BMT ceramic rod the ε_r and $\tan\delta$ values measured by the

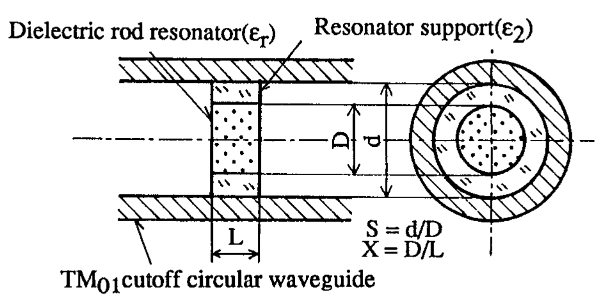


Fig. 1. Configuration of a $TM_{01\delta}$-mode dielectric rod resonator

dielectric rod resonator method[6] are shown in Fig. 2, from which the τ_r value of -13ppm/K at 20K is estimated on assumption that τ_α = 5.5ppm/K is constant in the range 20 to 300K. For the foamed polystyrene the τ_2 value is -8.4 ppm/K which was measured near room temperature. For the YBCO the measured results of surface resistivity *Rs* is shown in Fig. 3 together with that of the copper plated brass[7].

The appropriate dimension ratios have already been determined to realize high-Q_u and appropriate separation from neighboring modes; that is, $S = d/D = 1.5$ and $X = D/L = 1.25$ in the case of $\varepsilon_r = 24$[5]. Then more appropriate dimension ratio *S* will be determined to realize τ_f = 0ppm/K by using Eqs. (1)~(3) and the material parameters described above. Fig. 4 shows the calculated results for A_r, A_D, A_L, A_2 and A_c as a function of *S* when $\varepsilon_r = 24$, $\varepsilon_2 = 1.03$ and $X = 1.25$. Using these values, the τ_f values versus *S* were calculated for both cases of a YBCO cylinder having τ_c = 10ppm/K and a copper plated brass cylinder having τ_c = 20ppm/K. These results are shown in Fig. 5, from which we obtain τ_f = 0ppm/K at S =1.5 in the case of τ_c = 10ppm/K (YBCO) and at S =1.45 in the case of τ_c = 20ppm/K(copper). For these two $TM_{01\delta}$ mode dielectric resonators the Q_u values were calculated at 12GHz by using the measured values of $\tan\delta$ and *Rs*. These results are shown in Fig. 6 together with ones calculated for two TE_{011} -mode empty cavities[8] constructed from YBCO and copper, respectively. Furthermore the measured results of f_0 and Q_u for these $TM_{01\delta}$-mode dielectric resonators are also shown in Fig. 6 together with the Q_u values measured for TE_{011} -mode empty copper cavity. In the experiment, excitations of $TM_{01\delta}$-mode at input and output ports were performed by monopole antennas as shown in Fig. 7. For these two $TM_{01\delta}$-mode dielectric resonators the measured τ_f values are 1.7ppm/K in the range 20 to 300K, and is much smaller than -18ppm/K

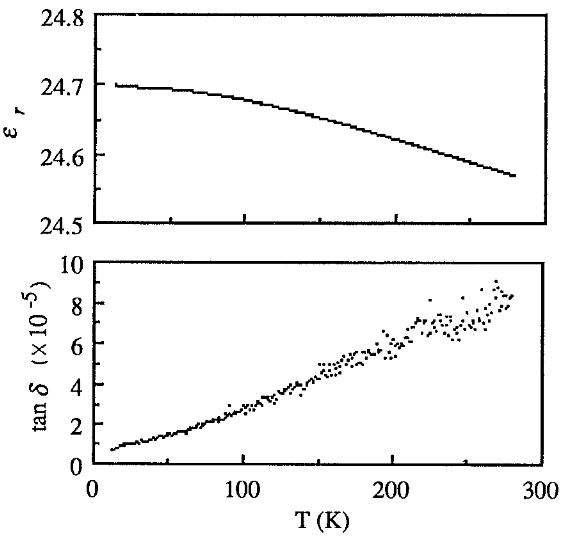


Fig. 2. Measured results of ε_r and $\tan\delta$ for a BMT ceramic rod

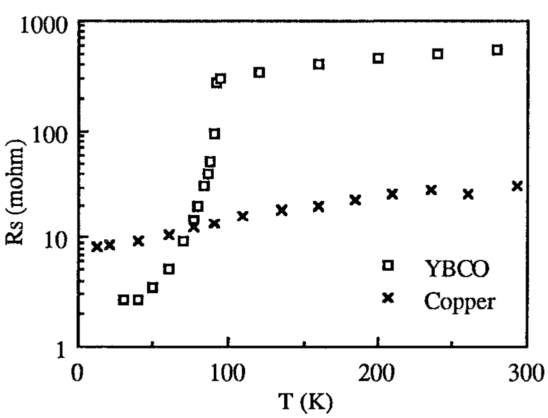


Fig. 3. Measured results of *Rs* for a YBCO and a copper plated brass

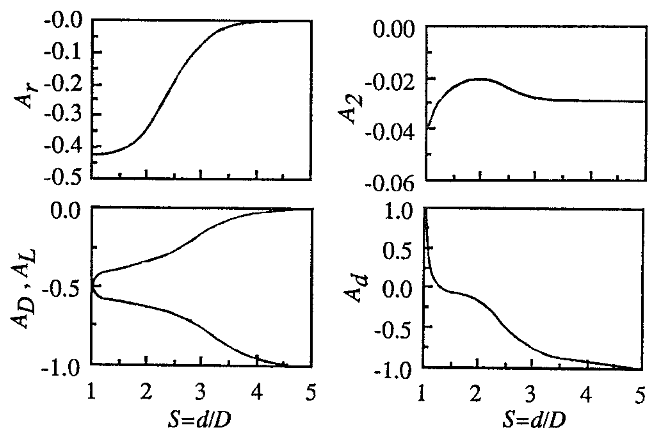


Fig. 4. Calculated results of the numerical constants in Eqs. (3) in the case of ε_r=24, ε_2=1.03 and X=1.25.

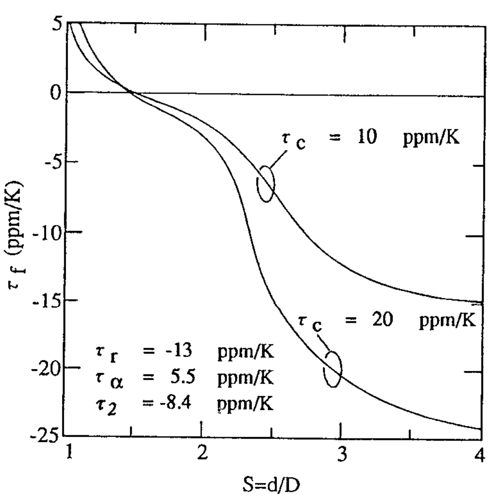


Fig. 5. Calculated results of τ_f in the case of ε_r=24, ε_2=1.03 and X=1.25.

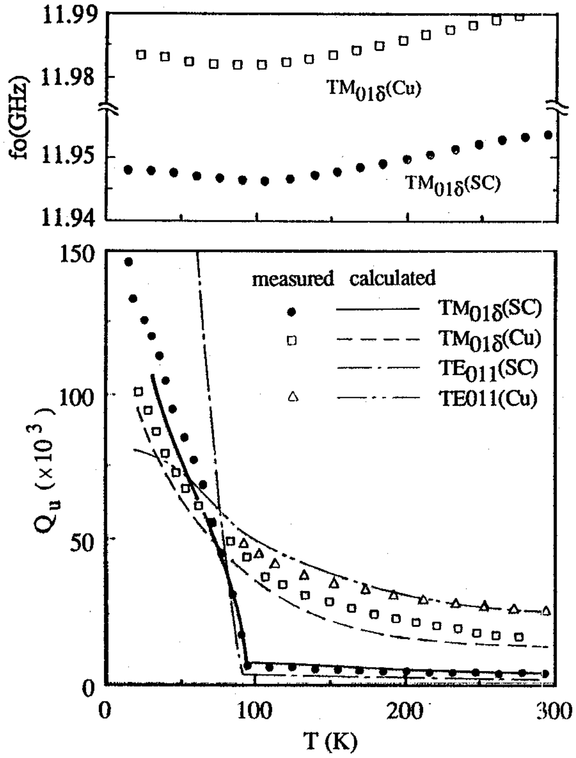


Fig. 6. Resonant frequencies and Q_u values of High-Q resonators

measured for the TE_{011} -mode copper cavity. For the $TM_{01\delta}$ -mode dielectric resonator with the YBCO cylinder the measured Q_u value is 150,000 at 20K, which is higher than Q_u = 100,000 for the copper cylinder case.

III. FILTER DESIGN

Fig. 7 shows a structure of a 2-stage bandpass filter used for experiment. Two $TM_{01\delta}$ resonators are oriented axially with a space of $2M$ in the YBCO cylinder having length of 23.5mm and are excited by monopole antennas which are fixed in copper cylinders. A filter housing is fabricated from copper because of good thermal conduction. The maximally flat type bandpass filter was designed with 3dB bandwidth 36MHz at 11.958GHz. The coupling coefficient between the resonators $k = 2.12\times10^{-3}$ is obtained when $2M$ = 10.8mm which is calculated numerically[5] and the external Q(Q_e) of 470 for each resonator is determined experimentally at room temperature. Fig. 8 shows the temperature dependence of k due to those of D, L, d, ε_r and ε_2 . When the filter is cooled from 300K to 20K, the decrease of k is 1.5%, which corresponds to only 0.6MHz reduction in 3dB bandwidth of 36MHz. Fig. 9 shows the f_0 and Q_e values measured as a function of the spacing between the monopole and the resonator l for the three cases of the monopole length l_p .The

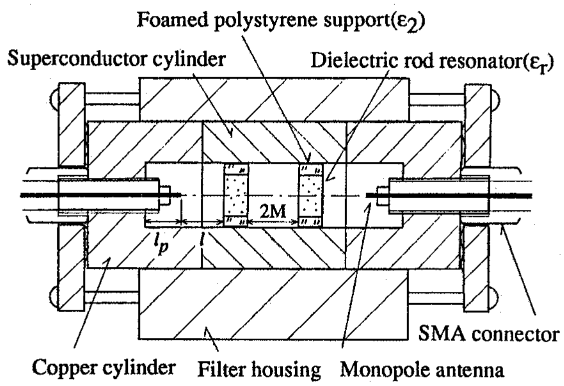


Fig. 7. Structure of a 2-stage bandpass filter

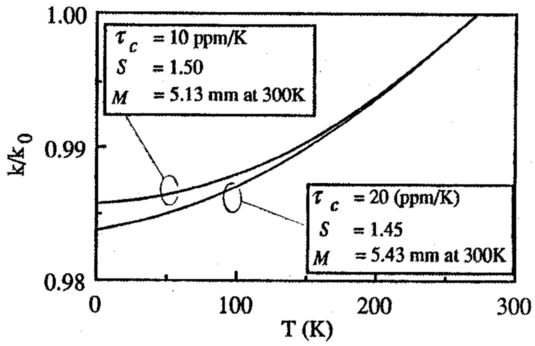


Fig. 8 Temperature dependence of coupling coefficient k
D = 7.2mm, L = 4.0mm at 300K
τ_α = 5.5 ppm/K, $k_0 = 2.12\times10^{-3}$

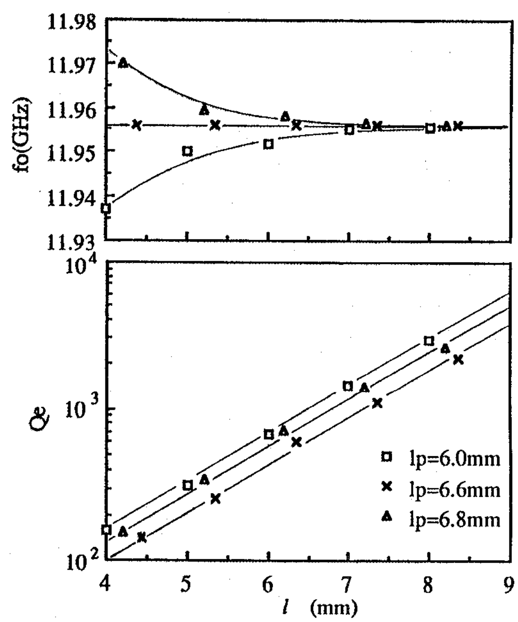


Fig. 9. Measured results for Q_e values versus l

case l_p = 6.6mm is the most suitable for the filter structure, because f_0 is invariant even if l changes with temperature. The measured transmission and reflection responses of this filter are shown in Fig. 10 by solid lines for 20K and by broken lines for 300K. Any adjustment of the filter was not performed at low temperatures after the filter is adjusted finely at room temperature. When the filter is cooled from 300K to 20K the center frequency is decreased by 5MHz and the insertion loss IL_0 at the center frequency is reduced from 1.8 dB to about 0dB, which was too small to be measured accurately. Fig. 11 shows the measured wide-band response. The resonant frequencies calculated for several resonant modes of the single resonator are indicated on the top of the figure. The good spurious response was realized because the resonant modes except TM_0-modes were suppressed by the monopole antennas. Fig. 12 shows measured results for the center frequency and IL_0 versus temperature. The temperature coefficient of the center frequency is 1.2ppm/K over 20~300K. The IL_0 value decreases rapidly below 80K.

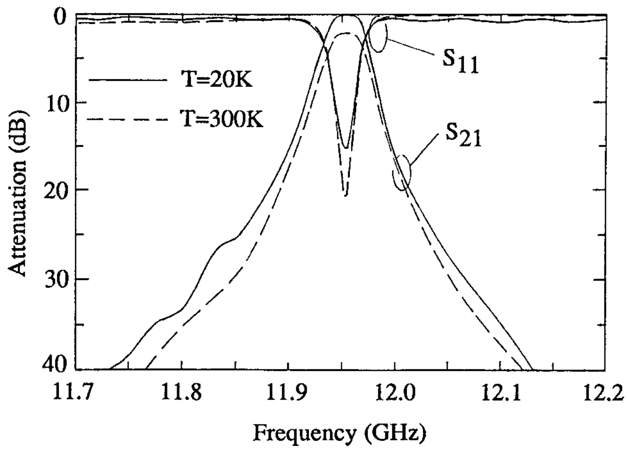


Fig. 10. Transmission and reflection responses of the filter

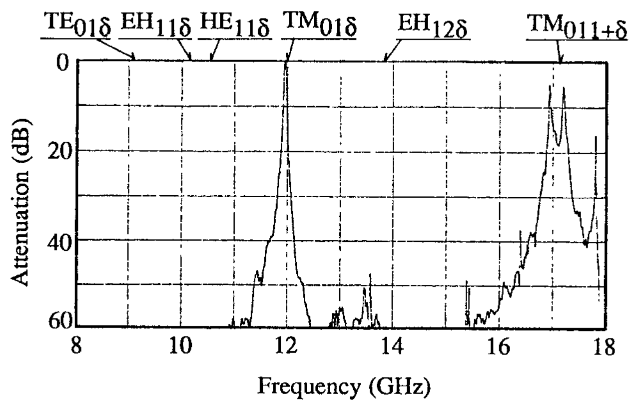
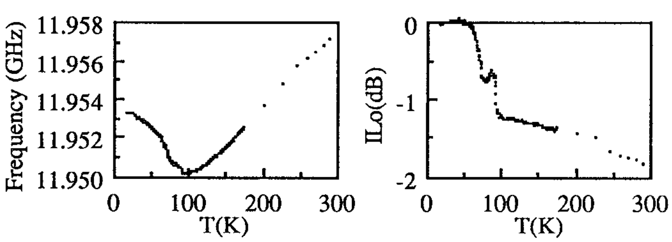


Fig. 11. Wide-band response of the filter



(a) Center frequency (b) IL_0

Fig. 12. Measured results for the center frequency and insertion loss IL_0 versus temperature

IV. CONCLUSION

A maximally flat type bandpass filter using two $TM_{01\delta}$-mode dielectric rod resonators oriented axially in a high-Tc superconductor cylinder was designed with 3dB bandwidth 36MHz at 11.958GHz. The center frequency shifted only 5MHz and the insertion loss IL_0 at the center frequency reduced from 1.8dB to about 0dB, which was too small to be measured accurately, when the filter is cooled from room temperature below 50K.

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