Third-order Intermodulation Measurements for Microwave Bandpass Filters of Thin Film High-temperature Superconductors

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Abstract

A major barrier to the application of high-temperature superconducting microwave filters is their power-handling capability. To clarify the key parameters for improving the power-handling capability of rf (radio frequency) filters based on high-temperature superconductors with microstrip structures, we synthesized bandpass filters with different layouts using several kinds of thin film high-temperature superconductors and subjected them to third-order intermodulation measurements. The experimental results indicate that increasing the film thickness and utilizing MBE-grown films of $NdBa_2Cu_3O_7$ are effective ways to obtain microstrip filters that can handle high power.

1. Introduction

For passive rf (radio frequency) filters, the use of superconductors can improve filter performance and enable miniaturization [1]. Passive microwave filters that use thin films of high-temperature superconductors (HTS) are now being widely used in the receivers of wireless communication systems because of their low insertion loss and high selectivity [1], [2]. Most such filters are composed of many resonators with microstrip arrangements, which reduce filter size while retaining superior performance. Currently, however, HTS microstrip filters are not used in transmitters because of the power-handling limitations imposed by nonlinear effects [3]. Several HTS filters for high-power operation have been reported [4]-[6] but their configurations are very different from those for the microstrip filters successfully used in receiver systems [1], [2] and are not suitable for making highly integrated miniaturized filters with a few tens of resonators.

For transmitter applications, the intermodulation generated by the nonlinearity of the superconducting filters should be suppressed to permit the use of high input power. In particular, third-order intermodulation (IM3) is a serious problem because it produces spurious signals within the passband of the filters. For example, when two input signals with frequencies f_1 and f_2 are applied to a filter, we get only two output signals with frequencies f_1 and f_2 if the filter has no nonlinearity. These output signals are called fundamental signals. If the filter does have some nonlinearity, however, we get various output signals with frequencies that differ from f_1 and f_2 in addition to the fundamental signals. The additional signals, which are generated by intermodulation caused by the nonlinearity of the filter, include signals with frequencies of $2f_1 - f_2$ and $2f_2 - f_1$ caused by IM3. The IM3 signals appear in the passband of the filter as spurious signals if f_1 and f_2 are in the passband and if $|f_1 - f_2|$ is small enough.

A convenient quantitative measure of nonlinearity is the third-order intercept, *IP3*, which is defined as the input power at which extrapolations of the fundamental and IM3 signal curves intersect [3]. High *IP3* values indicate low nonlinearity and better power-handling capability. Typical values of *IP3* reported for HTS microwave bandpass filters with the higher selectivity are lower than 40 dBm at 70 K. For transmission filters in base stations for mobile telephone services, we need *IP3* as high as 70 dBm. To expand the usage of superconducting microstrip filters in microwave transmission components, it is essential to clarify the key parameters that improve the *IP3* of HTS microstrip filters. In the present work, we took two approaches.

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The first approach was to investigate the effect of resonator geometry on *IP3*. The geometry of the filter's resonators is likely to affect the power-handling capability of the filters by varying the densities of the rf currents in the resonators. We examined the effect of resonator geometry on *IP3* by fabricating microstrip bandpass HTS filters with different resonator line widths and film thicknesses and assessing the *IP3* of the filters via IM3 measurements.

The second approach was to investigate the effect of film quality on *IP3*. This approach was based on the expectation that *IP3* might be improved by using thin HTS films with better properties than currently available ones. Recently it has been reported that large-area thin films of $(RE)Ba_2Cu_3O_7$ with rare-earth elements (REs) are being produced for microwave applications by technique based on molecular-beam epitaxy (MBE) with metal-element beam fluxes whose densities are strictly controlled by spectroscopic methods [7]. We fabricated sample filters and performed IM3 measurements on the films obtained by MBE growth and compared the results with values for commercially available films.

2. Experimental

2.1 IM3 measurements

IM3 measurements were carried out using two input signals with frequencies of 2.000 and 2.010 GHz using the experimental setup shown in **Fig. 1**. The two signals had equal amplitudes. The filter was assembled in a gold-plated oxygen-free high-purity copper package. The packaged filter is labeled as the device under test (DUT) in Fig. 1. The bandpass filter BPF-1 cut the higher harmonics generated by the power amplifiers. The center frequency and the 3-dB bandwidth of BPF-1 were 2 GHz and 100 MHz, respectively. The other bandpass filter, denoted BPF-2, was placed to allow the spectrum analyzer to measure the IM3 signal at levels as low as –100 dBm without saturation by the fundamental signal in the measured range of the input power level. The sensitivity improvement achieved by BPF-2 in the measurement setup was crucial to the success of this study. BPF-2 was composed of three tunable bandpass filters connected in series: each had a 3-dB bandwidth of 100 MHz. The center frequencies of the three filters, between 1800 and 2000 GHz, were set to optimize the sensitivity of the whole setup.

2.2 Filter fabrication

We designed 3-pole Chebyshev bandpass filters that use coupled hairpin resonators with line width *w* and pairs of feed lines with characteristic impedance of 50 Ω. A typical layout is shown in **Fig. 2**. The

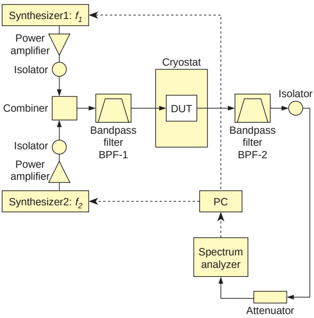

Fig. 1. Schematic diagram of experimental setup for third-order intermodulation measurements of a superconducting bandpass filter, labeled DUT (device under test).

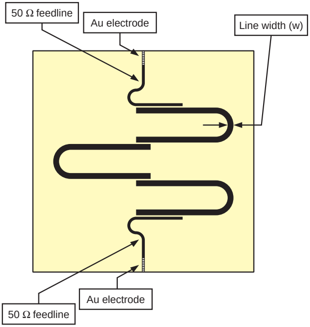

Fig. 2. Layout of a 3-pole microstrip bandpass filter composed of resonators with line width *w* and feed lines with the characteristic impedance of 50 Ω; electrodes formed by Au evaporation.

design parameters of the filters were center frequency of 2 GHz, passband width of 100 MHz, and passband ripple of 0.2 dB. We designed filters with *w* of 0.5 and 1 mm by a conventional method [8] using a circuit simulator and electromagnetic analysis. The filters were fabricated by a standard photolithographic process and Ar ion milling from double-sided films of $YBa_2Cu_3O_7$ (YBCO) and $NdBa_2Cu_3O_7$ (NBCO) on MgO substrates (35 mm × 35 mm); substrate thickness *h* was 0.5 mm. The YBCO films were commercially obtained. The NBCO films were grown by MBE [7]. On the ends of the filter feed lines, we formed ohmic electrodes with evaporated Au films (200 nm thick) as shown in Fig. 2. After the fabrication processes, *w* and film thickness *t* of the filters were measured with a profile meter.

3. Results and discussion

3.1 Filter characterization

The frequency dependencies of the magnitudes of S_{12} and S_{11}, the elements of the scattering matrix, the so-called *S* parameters, of an YBCO filter are plotted in **Figs. 3(a)** and **(b)** and **(c)**, respectively. As shown here, the transmission properties of the filters exhibited Chebyshev characteristics with insertion loss under 0.1 dB, typical passband ripple of 0.5 dB, and a passband width between 110 and 120 MHz. These values are consistent with the design parameters described above. The reflection properties in Fig. 3(c) have three poles whose frequencies exhibit reasonable agreement with the results calculated using the circuit simulator and electromagnetic analyzer. The measured frequency responses verified the design and fabrication procedures used in this study.

3.2 IM3 measurements

Figure 4 shows a typical result for IM3 measurement. The amplitude of the input signal (denoted "power in") was measured at the input port of DUT in Fig. 1. The amplitude of the output signal (denoted "power out") was obtained from the value measured at the spectrum analyzer after correction of the insertion loss of the whole signal line between the output port of DUT and input port of the analyzer. The input-power dependences of the amplitude of the fundamental signal and the IM3 signal fit well to straight lines with slopes of 1 and 3, respectively, as expected from a simple consideration [3]. To determine *IP3*, we used slopes of 1 and 3 in extrapolating the fundamental and intermodulation signals, respectively [3], as seen in Fig. 4. The amplitude of the input power at

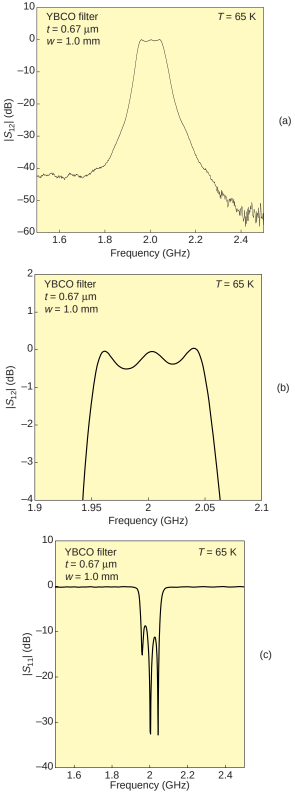

Fig. 3. Frequency dependences of (a) $|S_{12}|$, (b) $|S_{12}|$ in the passband region and (c) $|S_{11}|$ measured at 65 K for a 3-pole microstrip bandpass filter fabricated on a film of $YBa_2Cu_3O_7$ (YBCO) with thickness t = 0.67 µm and line width w = 1.0 mm.

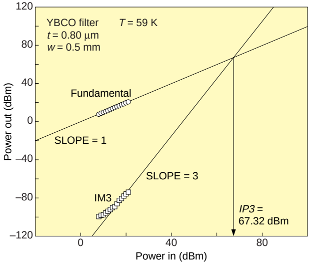

Fig. 4. Input-power dependences of the amplitude of the fundamental signal (open circles) and the third-order intermodulation signal (IM3) (open squares) measured at 59 K for a 3-pole microstrip bandpass filter fabricated on a film of $YBa_2Cu_3O_7$ (YBCO) with thickness t = 0.80 µm and line width w = 0.5 mm. The solid straight lines are the fitting results for the fundamental signal data and IM3 data with slopes of 1 and 3, respectively. The amplitude of the input power at the crossing point of the two lines is 67.32 dBm, which represents the third-order intercept *IP3* for the filter.

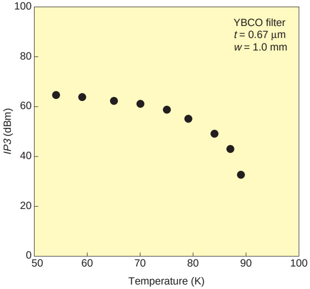

Fig. 5. Temperature dependence of the third-order intercept *IP3* for a 3-pole microstrip bandpass filter fabricated on a film of $YBa_2Cu_3O_7$ (YBCO) with thickness t = 0.67 µm and line width w = 1.0 mm.

the crossing point of the two lines gives *IP3* for the filter.

A typical temperature dependence plot of *IP3* for a YBCO filter is shown in **Fig. 5**. As the temperature decreased from the superconducting transition temperature to 70 K, *IP3* increased rapidly. Below 70 K, it was basically saturated. The highest value of *IP3* observed was +67.32 dBm at 59 K, which is about 30 dB higher than typical values reported for microstrip hairpin filters based on superconducting films [9]. Note that this comparison may not be completely valid because of differences in the passband widths, namely external *Q* values, and the numbers of poles. For example, relatively high *IP3* values have been reported for several filters designed for high-power handling purposes with small numbers of poles [10], [11].

Figure 6 plots the thickness dependences of *IP3* for YBCO filters with w = 0.5 and 1.0 mm by closed and open squares, respectively. The measured *IP3* for the filters with w = 0.5 mm at 70 K increased from +53 to +65 dBm as t was increased from 0.62 to 0.80 µm. The data for the filters with t around 0.6 µm indicate

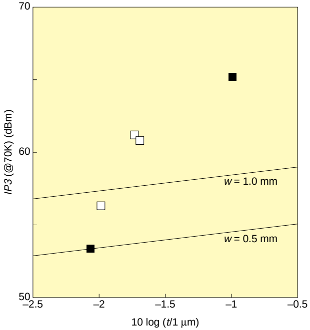

Fig. 6. Plot of measured values of *IP3* at 70 K as a function of film thickness t for 3-pole microstrip bandpass filters fabricated on films of $YBa_2Cu_3O_7$ (YBCO) with line widths w = 0.5 and 1.0 mm. The data for the filters with w = 0.5 and 1.0 mm are denoted by closed and open squares, respectively. The solid lines represent the calculated values for w = 0.5 and 1.0 mm normalized by the measured value for the filter with t = 0.62 µm and w = 0.5 mm. The calculation is based on the theoretical work by Dahm and Scalapino [12].

that the filters with w = 1.0 mm yield *IP3* about 4 dB higher than that offered by the filters with w = 0.5 mm. These results suggest that the power-handling capability of superconducting filters can be improved by increasing t and w.

For superconducting microstrip resonators, Dahm and Scalapino theoretically deduced that *IP3* increases as the line width and film thickness increase [12]. Based on their study, we calculated the thickness dependences of *IP3* values for w = 0.5 and 1.0 mm normalized by the measured value for the filter with t = 0.62 µm and w = 0.5 mm. Following their theoretical study [12], we used a penetration depth λ = 0.22 µm for the calculation, which we considered to be an appropriate value for YBCO films at around 77 K. The calculation results are represented by the solid lines in Fig. 6. Here, the increase of about 4 dB in *IP3* with the increase in w from 0.5 to 1.0 mm is generally consistent with the theoretical expectation. On the other hand, the increase of about 10 dB in *IP3* with the increase in t from 0.62 to 0.80 µm is much larger than theoretically expected 1 dB increase. As shown in Fig. 6, we found that the measured *IP3* at 70 K increased from +53 to +65 dBm with an increase in t from 0.62 to 0.80 µm, which gives an increase of only 1 dB in *IP3* in the theoretical analysis. Our results suggest that the power-handling capability of superconducting filters can be quite effectively improved by increasing t. It may be noteworthy that an *IP3* value as large as 65 dBm at 77 K at 10 GHz has been reported for an YBCO film with a thickness as large as 3 µm [11]. At the present stage, the origin of the unexpectedly strong enhancement of *IP3* with the increase in t is not clear.

Figure 7 compares the temperature dependences of *IP3* for filters made from MBE-grown NBCO films with t = 0.55 µm with those created using commercial YBCO films with t = 0.63 µm. It should be noted that *IP3* for the NBCO filter was 2–5 dB higher than that for the YBCO filters as seen in Fig. 7 while t for the former was smaller than that for the latter. This result suggests that improving film quality is also effective in improving the power capability of rf filters based on thin HTS films. It is also noteworthy that the improvement in *IP3* increases with temperature. This result is consistent with the fact that the superconducting transition temperature for NBCO is higher than that for YBCO. The improvement in power-handling capability at higher temperatures may raise the operating temperatures of HTS filters for both receiving and transmission, resulting in smaller cryocoolers in the filter systems.

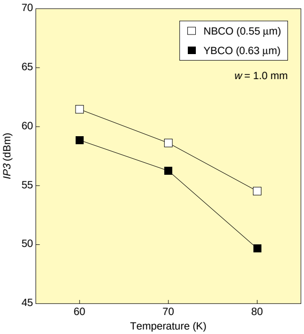

Fig. 7. Temperature dependences of the third-order intercept *IP3* for 3-pole microstrip bandpass filters with line width w = 1.0 mm fabricated on a film of $NdBa_2Cu_3O_7$ (NBCO) grown by molecular-beam epitaxy with thickness t = 0.55 µm and a commercially obtained film of $YBa_2Cu_3O_7$ (YBCO) with t = 0.63 µm.

4. Conclusion

We performed third-order intermodulation measurements on microstrip bandpass filters with different layouts made from several kinds of thin film high-temperature superconductors. The improved sensitivity of the measurement setup described here achieved by selective reduction of the fundamental signals allowed us to successfully measure the IM3 signals for the filters. We found that *IP3* for the filters was effectively enhanced by increasing film thickness t. For the YBCO filters, *IP3* at 70 K increased from +53 to +65 dBm as t was increased from 0.62 to 0.80 µm. Moreover, filters made from MBE-grown NBCO films yielded *IP3* values 2–5 dB higher than filters made from commercially obtained YBCO films.

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