

High T_c superconducting CPW bandstop filters for radio astronomy front ends

S. Wallage, J. L. Tauritz, G. H. Tan, P. Hadley and J. E. Mooij

Abstract— We have designed and tested a superconducting coplanar waveguide (CPW) bandstop filter consisting of 8 coupled line sections at a center frequency of 1.53 GHz. A packaged 94.7% bandwidth low pass Chebychev design yielded a filter with a center frequency of 1.56 GHz, less than 1.2 dB insertion loss in the passband and better than 28 dB rejection at 20 Kelvin. With a skirt selectivity of 1.53 ($=BW_{1\text{ dB}}/BW_{28\text{ dB}}$) and low insertion loss this filter is an excellent candidate for suppressing contiguous spurious signals in cooled low-noise receiving front ends.

I. INTRODUCTION

INCREASED usage of the low GHz electromagnetic spectrum has stimulated the development of new microwave components. In particular the low loss characteristics of high T_c superconductors have been exploited to fabricate filters and antennas with superior performance. A good example of the use of high T_c materials to improve filter performance is the 19 pole bandpass filter reported by Conductus. [1]

Initially our work concentrated on bandpass filters for use at radio astronomy sites. Actual developments at the major synthetic aperture telescope at Westerbork in the Netherlands prompted us to shift to bandstop and notch filters in response to the interference to astronomical observations caused by a cluster of Russian navigation satellites, known as the Glonass system [2], in the frequency band 1560-1630 MHz. It was clear that a means must be found to reject the Glonass signals without attenuating signals at nearby frequencies coming from distant sources in the universe. Since the radio telescope receivers are already cooled to 20 Kelvin to reduce the noise in the semiconductor electronics, high T_c materials are very attractive for this application. In the frequency band ranging from 1450-1610 MHz no astronomical measurements are performed, so the stopband was specified in this range. Other work on high T_c bandstop filters have been reported by STI who used a 6 bank optically switchable bandstop filter [3] and Lancaster *et al.* [4] who employed a lumped element approach.

The bandstop filter template is shown in Fig. 1. For this filter several design approaches were considered. Initially a lumped element filter realisation was investigated. Unfortunately it was found that the discrete components of the filter, the inductors and capacitors, did not behave as

ideal elements over the whole frequency range of the filter. Parasitic effects always caused a deviation from the desired ideal response. This is a general problem with bandstop filters, which usually have a low insertion loss over a fairly broad passband and high rejection in a narrow stopband. In general, bandstop filters offer much less design flexibility than bandpass filters. [5, p. 163] Realising discrete filters to satisfy the specifications over the whole frequency range turned out to be very difficult.

Distributed filters using CPW transmission lines proved more tractable. Although in the majority of cases microstrip transmission line is used, we found the use of coplanar waveguide more suited for the filter for a technological reason: it was impossible to fabricate vias in the high T_c substrates and we wanted to use our cold wafer prober for accurate and calibrated measurements. Coplanar waveguide structures facilitate increasing packing density, without the need for thin substrates as is the case for microstrip transmission lines. In addition, high performance microstrip transmission lines require a superconducting groundplane and integration with active elements should be possible without vias. The multi-mode character of coplanar waveguides is, however, a major drawback and can only be solved using airbridges or grounded CPW. Unfortunately, microwave simulation programs have extensive libraries for microstrip transmission lines and only limited support for CPW-structures.

Several types of substrates are available for growing high T_c thin films. MgO substrates have the advantage that their relative dielectric constant is very close to that of alumina, so that standard design rules are applicable. LaAlO₃ is available up to 76.2 mm wafer diameter and, due to a higher dielectric constant, leads to a size reduction of ≈ 1.5 with respect to MgO. Many manufacturers grow YBa₂Cu₃O₇ on LaAlO₃. Impedance values for coplanar waveguide transmission lines on LaAlO₃ range from 25 Ω to 85 Ω , which is sufficient for our application.

II. THE FILTER DESIGN

Several design issues have been taken into account: 1) realization with CPW transmission lines, 2) compactness and 3) robustness (insensitive to fabrication tolerances). We started by considering an elliptic design, because the steep fall-off at the transition from passband to stopband could be realized with an elliptic filter. A five pole elliptic filter design that is sufficient can be found in the *Handbook of Filter Synthesis*. [5, p. 216] For the moderate bandwidth of 10.46% not all types of transmission line filters can be used due to the limited range of impedance values. A basic building block for an elliptic bandstop filter is depicted in

S. Wallage and J. L. Tauritz are with the Department of Electrical Engineering, Delft University of Technology at Delft, The Netherlands

G. H. Tan is with the Netherlands Foundation for Research in Astronomy (NFRA) at Dwingeloo, The Netherlands

S. Wallage, P. Hadley and J. E. Mooij are with the Department of Applied Physics, Delft University of Technology at Delft, The Netherlands.

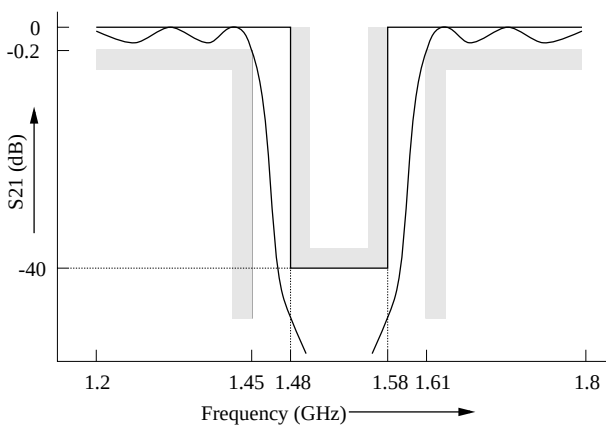


Fig. 1. The bandstop filter specification

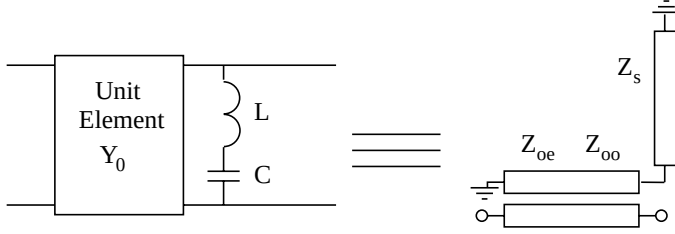


Fig. 2. S -plane realization of an elliptic element

Fig. 2. [6, pp. 159-170] By folding five different sections for a five pole design, an area of $3/4 \lambda$ (≈ 42 mm) is required. The design is thus rather large and an elliptic function design is sensitive to the position of both poles and zeroes. So the design is potentially non-robust and large, in violation with two of the initial design goals.

The approach we eventually selected was based on a variant of a parallel coupled line Chebychev filter which proved realizable using a compact hairpin like topology. An expert system, based on the theory of Horton and Wenzel [7] and implemented within Hewlett Packard's Microwave Design System [8], was used to find a low-pass non-redundant prototype consisting of 8 unit elements (UE) and 7 inductances (Fig. 3) having a 7 pole Chebychev response. The S -plane equivalence of the cascade of a unit element and an inductance is a parallel coupled line with one end shorted and the other end open (Fig. 4). [9, p. 98] This was used as a basic building block by applying the transformation

$$Z_{oe} = Z_0 \left[Y_0 L + 1 + \sqrt{Y_0 L (Y_0 L + 1)} \right], \quad (1)$$

$$Z_{oo} = Z_0 \frac{Y_0 L + 1 + \sqrt{Y_0 L (Y_0 L + 1)}}{2Y_0 L + 1 + 2\sqrt{Y_0 L (Y_0 L + 1)}}. \quad (2)$$

To check the feasibility of the CPW-approach we first designed a five pole prototype at 3 GHz, which fits on a 10×10 mm² substrate. This prototype was described elsewhere. [10] Subsequently the filter's center frequency was scaled to 1.53 GHz by increasing the coupled line lengths. Based on the encouraging results achieved with the 3 GHz prototype, the number of coupled lines was increased to 8. Measurements on separate coupled lines showed excellent agreement with the library model in the Microwave Design

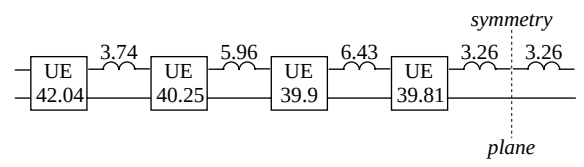


Fig. 3. Prototype 94.8% bandwidth low-pass filter

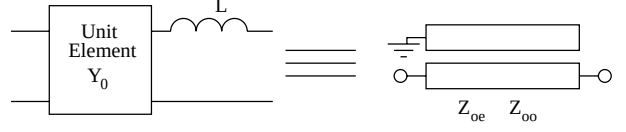


Fig. 4. S -plane equivalence

System, where only compensation for the phase velocity is needed. [10]

III. FILTER FABRICATION AND MEASUREMENT

A 2-inch LaAlO₃ wafer coated with 300 nm of YBa₂Cu₃O₇ was purchased from Cryoelectra, Wuppertal, Germany. The wafer was fabricated using a high pressure on-axis DC sputtering process. The wafer was cut into 4 pieces from which the filter was fabricated using wet etching. Goldwire bonding was performed to guarantee equal phases of the ground planes using a Kaijo FB118CH hybrid goldwire bonder. A photo of the filter can be seen in Fig. 5. A close up of the corner detail is sketched in Fig. 6. The filter was packaged in a copper box. Connection to ground was established by connecting the top cover to the ground strips on the substrate (see the parts in Fig. 5 denoted as GROUND). A tapered structure enable microstrip launchers to be connected to the CPW signal lines. After cooling down to 20 Kelvin the packaged filter was measured. The measurement result is shown in Fig. 7.

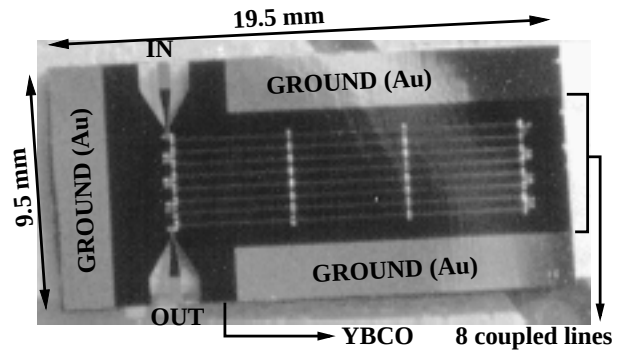


Fig. 5. Photo of the bandstop filter



Fig. 6. Close up of the coupling section

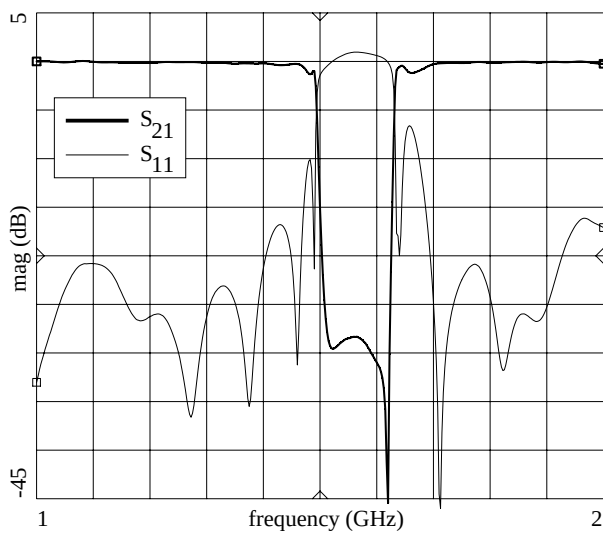


Fig. 7. Measurement of the bandstop filter

Clearly visible is the reduced bandrejection and the extra ripple near the stopband. A bandrejection of -28 dB is less than the desired -40 dB due to direct and parallel plate coupling from input to output. The extra ripple may be due to underetching (estimated $\approx 1.5 \mu\text{m}$) of the YBCO-layer. A very weak etch solution of HCl (0.04 % Vol.) was used. YBCO etches faster in the *ab*-plane than along the *c*-axis resulting in an underetch. [11] This underetch is responsible for an excessive reduction in impedance values, deteriorating the bandstop response and increasing ripple in the passband. The S_{11} exceeds zero in the stopband, because a room temperature calibration was performed. The accurate phase velocity of the CPW-transmission line was not known in advance resulting in a frequency shift from 1.53 up to 1.56 GHz.

IV. FINETUNING THE RESPONSE

To eliminate the influence of connectors and box it is desirable to measure the filter with the coplanar probes. To better approximate the design dimensions, dry etching should be carried out of the $\text{YBa}_2\text{Cu}_3\text{O}_7$ layer. The packaged filter should be redesigned, so that the in and output are placed diagonally on the substrate and parallel plate mode are suppressed, see Fig. 8. The alternating distance between CPW-ground plane and the copper box results in a series of impedance steps reflecting the parallel plate mode. The fabrication of the finetuned filter is in progress.

V. CONCLUSIONS

A coplanar waveguide bandstop filter has successfully been designed, fabricated and measured. At a center frequency of 1.56 GHz 8 coupled lines constitute a 7 pole filter having an insertion loss of less than 1.2 dB and a skirt selectivity of 1.53 with bandrejection better than 28 dB. The filter must be redesigned to operate at a center frequency of 1.53 GHz and the packaging should be improved to increase bandstop rejection. The coupled line

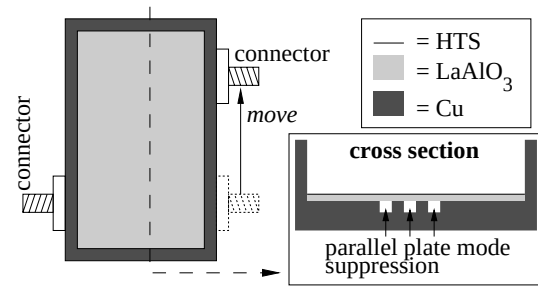


Fig. 8. Redesign of the package

filter fabricated in coplanar waveguide is a highly compact structure and can easily be extended to a higher order filter.

ACKNOWLEDGMENTS

The authors wish to thank D. van der Weg of Philips Semiconductors, Nijmegen for sample bonding.

REFERENCES

- [1] D. Zhang, G. C. Liang, Z. H. Lu, C. F. Shih, and M. E. Johansson, "A 19-pole Cellular Bandpass Filter using 75-mm Diameter High Temperature Superconducting Thin Films," *IEEE Microwave and Guided Wave Letters*, vol. 5, no. 11, pp. 405-407, Nov. 1995.
- [2] Y. G. Gouzhva, "High Precision Time and Frequency Dissemination with Glonass," *GPS World*, vol. 3, no. 7, pp. 40-49, July 1992.
- [3] N.O. Fenzi, K.F. Raihn, G.V. Negrete, E.R. Soares, and G.L. Matthaei, "An Optically Switched Bank of HTS Bandstop Filters," In *1994 IEEE MTT-S International Microwave Symposium Digest* [12], pp. 195-198.
- [4] M. J. Lancaster, J. C. Li, A. Porch, and N. G. Chew, "High Temperature Superconducting Lumped Element Resonator," *Electronic Letters*, vol. 29, no. 19, pp. 1728-1729, Sept. 1993.
- [5] A. I. Zverev, *Handbook of Filter Synthesis*, John Wiley and Sons Inc., New York (U.S.A.), 1967.
- [6] L. Young, *Microwave Filters using Parallel Coupled Lines*, Artech House Inc., Dedham (U.S.A.), 1972.
- [7] M. C. Horton and R. J. Wenzel, "General Theory and Design of Optimum Quarter Wave TEM-filters," *IEEE Trans. Microwave Theory Tech.*, vol. 13, no. 5, pp. 316-327, May 1965.
- [8] K. Mouthaan, U. Akpınar, J. Willms, P. Snoeij, and J. L. Tauritz, "Automated Planar Filter Synthesis Embedded in HP's Microwave Design System," in *Proceedings (esa-WPP-097)*. Nov. 1995, pp. 81-94, ESA.
- [9] A. Matsumoto, *Microwave Filters and Circuits*, Academic Press, New York (U.S.A.), 1970.
- [10] S. Wallage, J. L. Tauritz, P. Hadley, and J. E. Mooij, "High T_c Superconducting CPW Bandstop Filters," *IEEE Microwave and Guided Wave Letters*, vol. 6, no. 8, pp. 292-294, Aug. 1996.
- [11] R. P. Vasquez, M. C. Foote, and B. D. Hunt, "Nonaqueous Chemical Depth Profiling of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$," *Applied Physics Letters*, vol. 54, no. 11, pp. 1060-1064, Mar. 1989.
- [12] *Proc. of the IEEE Trans. Microwave Theory Tech. Symp.* Institute of Electrical Engineers, New York (U.S.A.), May 1994.