HIGH-TEMPERATURE SUPERCONDUCTIVE PASSIVE MICROWAVE DEVICES*

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ABSTRACT

Two important classes of passive superconductive microwave devices are described that have been recently demonstrated using thin films of the high-temperature superconductor $YBa_2Cu_3O_{7-x}$. The devices include tapped-delay-line transversal filters with multigigahertz bandwidths and with time-bandwidth products as large as 30, and narrowband (less than three-percent bandwidth) microstrip filters. These devices illustrate the potential performance advantages superconductive thin films offer to the designer of a high-frequency, wide-bandwidth analog signal processing system.

INTRODUCTION

Passive superconductive microwave devices exploit the low conductor loss of a superconductor. These devices are particularly suited to high-frequency, wide-bandwidth analog signal processing applications [1]. Recent advances in thin-film deposition techniques for high-temperature, copper-oxide superconductors have made possible the demonstration of passive microwave components on substrates as large as 50-mm diameter. Figure 1 diagrams the current state of the art in thin films of the high-temperature superconductor $YBa_2Cu_3O_{7-x}$ (YBCO) by plotting the surface resistance as a function of frequency for thin films of YBCO as well as several benchmark curves (copper at 77 K, superconducting niobium at 4.2 K, and superconducting Nb_3Sn at 4.2 K). Because YBCO films are chemically sensitive and the YBCO can degrade during patterning, especially at the edges of a transmission line where the currents peak, measured surface resistance is shown for both patterned and unpatterned films. The cross-hatched region represents the surface resistance obtained on patterned films used in this work. To illustrate the potential performance of YBCO, theoretical curves obtained using the standard two-fluid model for the surface resistance of YBCO [2] are also plotted. The parameters used were $\lambda_o = 150$ nm, $T_c = 93$ K, and $\sigma_n = 2 \times 10^6\ \Omega^{-1}\ m^{-1}$. It should be noted that the Siemens/Wuppertal data point at 77 K is within a factor of two of the prediction of the two-fluid model if the actual T_c of that film is used in the model.

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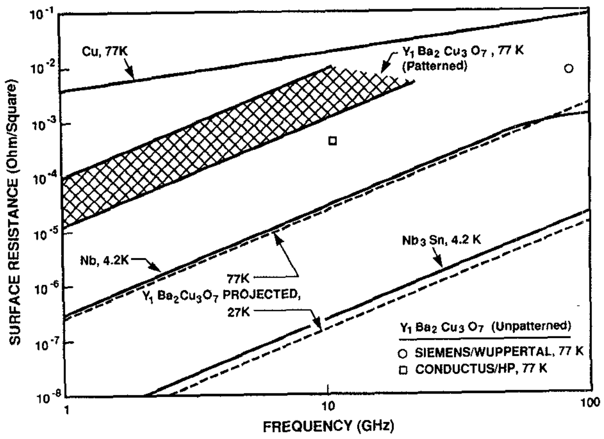

Figure 1 - Surface resistance versus frequency for cooled copper and for superconducting niobium, Nb_3Sn, and YBCO. Measured values for both patterned and unpatterned YBCO films are shown. Theory curves for YBCO were generated using the two-fluid model.

The low conductor loss of a superconductor can be used quite readily in two general classes of passive microwave devices. Long delay lines take advantage of the low propagation loss and dispersionless nature of a thin film superconductor, and resonator-based filters take advantage of the large conductor quality factor that can be obtained using thin-film superconductors.

TAPPED-DELAY-LINE CHIRP FILTERS

Compact transversal filters in the form of tapped delay lines have previously been fabricated from superconducting niobium to operate with multigigahertz signal processing bandwidths [3,4]. One example of a fixed-tap-weight transversal filter is a linearly frequency modulated delay line or chirp filter. Figure 2 shows the architecture of a chirp filter made using superconducting striplines with a cascaded series of backward-wave couplers, in this case forming a down-chirp. Each coupler has a peak response at the frequency for which it is 1/4 wavelength long. By making the length of the couplers proportional to the reciprocal of the length down the line, the filter has a local resonant frequency which is a linear function of delay. Design of the stripline chirp filters is based on coupling of modes theory [3].

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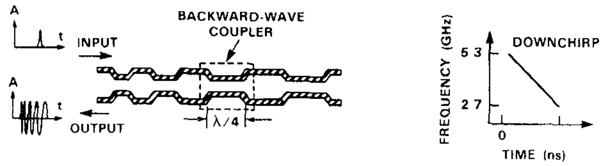

Figure 2 - Chirp filter architecture and instantaneous frequency of the impulse response of a downchirp filter. A typical superconducting niobium-on-silicon chirp filter can contain hundreds of backward-wave couplers.

Figure 3 shows the layout of the most recent chirp filter designed for implementation in YBCO. This device has 11.5 ns of dispersive delay with 48 backward-wave couplers and 14 ns of total delay. The device has a bandwidth of 2.6 GHz and a time-bandwidth product of 30. The chirp-filter design incorporates a tapered-line impedance transformer so that the tapped portion of the filter could be implemented with 40-ohm, 120-µm-wide lines on 50-mm-diameter, 500-µm-thick $LaAlO_3$ substrate. The use of 120-µm-wide line was crucial to the success of this design based on previous work with YBCO delay lines [5]. The fabrication of narrow YBCO signal lines is very difficult due to film nonuniformities and defects introduced during photolithography and patterning.

Figure 3 - Layout of flat-weighted chirp filter with 11.5 ns of dispersive delay and 14 ns of total delay. Klopfenstein-taper impedance transformers make the transition between the narrow 50-ohm input lines and the wider 40-ohm tapped delay lines.

Figure 4 shows time-domain-reflectometry data taken at various temperatures on one of the two parallel striplines comprising the chirp filter shown in Fig. 3. This in-situ sputtered YBCO film [6], grown at Conductus on 50-mm-diameter $LaAlO_3$, had a uniform transition temperature of approximately 90 K. The device clearly functions at 88.5 K, although series resistance limits the performance somewhat at temperatures above 77 K. Note that the effects of kinetic inductance can be seen, with the 88.5 K response showing approximately 0.25 ns more delay. Above 92 K, the high resistivity of the line becomes obvious. Also there is an approximately 6% voltage reflection at the beginning of the tapered line (after about 7 ns of delay). Frequency-domain measurements indicate that the response at 77 K agrees with design to within a fraction of a decibel. Figure 5 is a plot of the down-chirp response to an input step function, with data at 92.2, 88.5, 77.3, and 17.1 K. Each of the 48 couplers is clearly visible. Again kinetic inductance effects are obvious at 88.5 K, adding approximately 0.5 ns to the delay. Recall that matched filters such as chirps require a phase match to within several degrees to be effective. Any temperature fluctuation at 88.5 K would perturb the match between filters, in addition to the increased loss present for temperatures near the transition temperature. Figures 6(a) and (b) are plots of the group delay (derivative of the phase versus frequency) of the up-chirp and down-chirp responses, respectively.

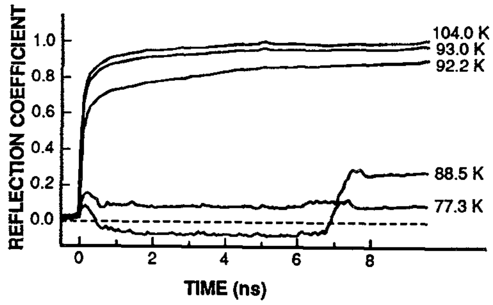

Figure 4 - Time domain reflectometry data taken at various temperatures on a single transmission line of the flat-weighted chirp filter shown in Fig. 3.

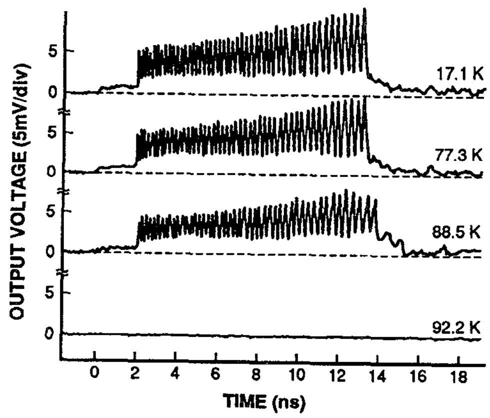

Figure 5 - Down-chirp response to a step input at various temperatures. Note the additional delay caused by kinetic inductance at 88.5 K.

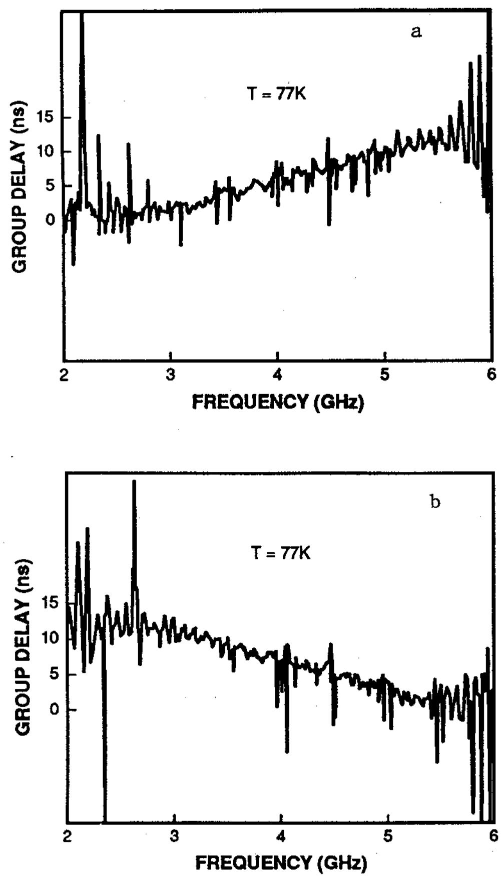

Figure 6 - Group delay as a function of frequency at 77 K for the YBCO chirp filter shown in Fig. 3 showing (a) the up-chirp response and (b) the down-chirp response.

Most analog signal processing structures are variations of the transversal filter. A tapped delay line can be used to implement matched filtering, correlation, and Fourier transformation. The number of information cycles gathered coherently in the filter determines the signal-processing gain, i.e., the time-bandwidth product. Figure 7 shows the near-term projections for the signal-processing gain available from various technologies compared to projections for YBCO based on the surface resistance calculated using the two-fluid model. For example, the equivalent digital signal processing capability of a Cray-2 computer (2 GOPS) would fall more than an order of magnitude short of the analog signal processing capability of the most current YBCO chirp device (shown as the triangular data point).

RESONATOR-BASED BANDPASS FILTERS

The Q of normal-metal microstrip lines is too low to support the low insertion loss and sharp filter skirts needed for channelizing microwave communication bands on communication satellites, where nearly lossless filters are required. Superconducting microstrip filters could eventually replace dielectrically loaded cavity filters with a significant reduction in weight of a multiplexing filter bank requiring dozens of filters. In addition, the potential exists to produce superconducting filters with much sharper filter skirts so that communication bands can be utilized more efficiently.

Figure 8 shows the layout for a four-pole filter design that operated at 4.8 GHz with a 1.3% bandwidth. This filter was redesigned from an original four-pole, 3%-bandwidth filter [7] to reduce the sensitivity of the filter to variations in linewidth and substrate dielectric constant. Figure 9 shows the measured filter response for this design using several different conductors at temperatures of 300 and 77 K. The filter was fabricated on 20-mil-thick $LaAlO_3$ using gold, silver, and postannealed coevaporated YBCO [8]. The YBCO filter had 1.0 dB of insertion loss at 77 K compared with 5.9 dB for the silver filter at 77 K and 10.6 dB of insertion loss for the gold filter at 300 K. Filters fabricated from YBCO using the previous 4.2 GHz, 3% bandwidth design had exhibited, at 77 K, a passband insertion loss as low as 0.3 dB compared to the 2.8-dB loss of similar gold metallic filters at the same temperature [7].

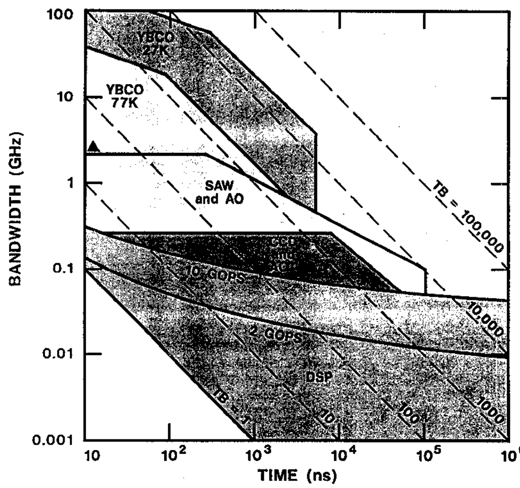

Figure 7 - Near-term projections of signal processing capabilities for various technologies [see Ref. 2]. Represented are digital signal processing (DSP), charge-coupled device (CCD), acoustic charge transport (ACT), surface acoustic wave (SAW), acousto-optic (AO), and superconducting delay lines using YBCO. Projections for YBCO are based on the theoretical values of surface resistance shown in Fig. 1. The triangular data point represents the time-bandwidth product of 30 for the most recently demonstrated YBCO tapped-delay-line chirp filter operated at 77 K (see Fig. 3).

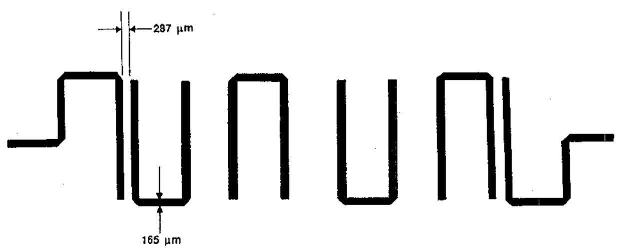

Figure 8 - Four-pole microstrip filter design for operation at 4.8 GHz with a 1.3% bandwidth

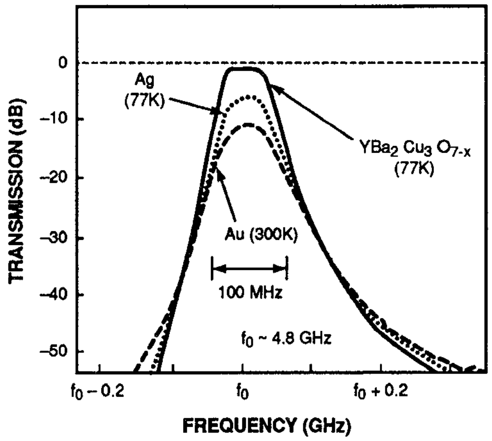

Figure 9 - Measured filter response of the design shown in Fig. 8 fabricated from gold (measured at 300 K), silver (measured at 77 K), and YBCO (measured at 77 K).

Due to inaccuracies in microwave CAD packages for large dielectric constants (ε_r ~24 for $LaAlO_3$), design of the bandpass filters was accomplished in a semi-empirical fashion [9]. A first iteration was designed using an existing CAD package. Line-line couplings were then measured on this design and used to adjust the CAD design to more closely match the actual filter parameters.

FUTURE RESEARCH

There are many materials issues that limit the performance or the ability to fabricate YBCO delay lines and bandpass filters. The design of YBCO delay lines is challenging because of the wide linewidths required by current patterning techniques, the chemical sensitivity of YBCO, the difficulty in depositing uniform YBCO over a 50-mm-diameter substrate, the high dielectric constant of $LaAlO_3$ substrate material, and the thickness of the available $LaAlO_3$ substrates (which necessitates large line-to-line spacings). Resonator-based filters are very sensitive to linewidth variations, their design for high dielectric constant or anisotropic substrate materials is difficult because of the current deficiencies of CAD routines, and shifts in resonator frequencies due to variations in the substrate dielectric constant or large kinetic inductance effects cannot be tolerated. In general, YBCO deposition techniques will continue to improve and new dielectric materials or combinations of dielectrics will be examined. Finally, the availability of thinner, large-area substrates and multilayer dielectrics will eventually allow much more complex circuits to be designed.

CONCLUSIONS

Two distinct classes of superconductive, passive microwave devices were demonstrated, both with a significant performance advantage over normal-metal versions of the same devices: long tapped delay lines and resonator-based bandpass filters. A stripline chirp filter was fabricated and operated at 77 K. The chirp filter design incorporates a tapered-line impedance transformer so that the tapped portion of the filter could be implemented with 40-ohm, 120-μm-wide lines on 50-mm-diameter $LaAlO_3$ substrate. This YBCO chirp filter has a 2.6-GHz bandwidth, a 4-GHz center frequency, and 11.5 ns of dispersive delay giving a time-bandwidth product of 30. The total transmission-line length of the chirp filter represents 14 ns of delay. Microstrip narrowband bandpass filters were also fabricated from thin films of YBCO and operated at 77 K with bandwidths ranging from 1 - 3% at 4.8 GHz. These devices were four-pole Chebyshev filters and were fabricated on 1.3 x 2.5 cm $LaAlO_3$ substrates. Both of these classes of microwave devices illustrate that the low conductor loss of superconducting materials makes it possible to build passive microwave devices that cannot be built with normal metal conductors. Operation of these superconducting devices is now possible at temperatures up to 77 K, opening up new opportunities for high-frequency, wide-bandwidth analog signal processing systems.

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REFERENCES

(1) R. S. Withers and R. W. Ralston, "Superconductive Analog Signal Processing Devices," *Proc. IEEE,* vol. 77, pp. 1247-1262, August 1989.

(2) W. G. Lyons and R. S. Withers, "Passive Microwave Device Applications of High-T_c Superconducting Thin Films," *Microwave Journal*, vol. 33, pp. 85-102, November 1990; and references therein.

(3) R. S. Withers, A. C. Anderson, J. B. Green, and S. A. Reible, "Superconductive Delay-Line Technology and Applications," *IEEE Trans. Magn.,* vol. MAG-21, pp. 186-192, March 1985.

(4) M. S. DiIorio, R. S. Withers, and A. C. Anderson, "Wide-Band Superconductive Chirp Filters," *IEEE Trans. Microwave Theory Tech.,* vol. 37, pp. 706-710, April 1989.

(5) W. G. Lyons, R. S. Withers, J. M. Hamm, A. C. Anderson, P. M. Mankiewich, M. L. O'Malley, and R. E. Howard, "High-T_c Superconductive Delay Line Structures and Signal Conditioning Networks," *IEEE Trans. Magn.,* to be published, March 1991.

(6) N. Newman, B. F. Cole, S. M. Garrison, K. Char, and R. C. Taber, "Double Gun Off-Axis Sputtering of Large Area $YBa_2Cu_3O_{7-x}$ Superconducting Films for Microwave Applications," *IEEE Trans. Magn.,* to be published, March 1991.

(7) W. G. Lyons, R. R. Bonetti, A. E. Williams, P. M. Mankiewich, M. L. O'Malley, J. M. Hamm, A. C. Anderson, R. S. Withers, A. Meulenberg, and R. E. Howard, "High-T_c Superconductive Microwave Filters," *IEEE Trans. Magn.,* to be published, March 1991.

(8) P. M. Mankiewich, J. H. Scofield, W. J. Skocpol, R. E. Howard, A. H. Dayem, and E. Good, "Reproducible Technique for Fabrication of Thin Films of High Transition Temperature Superconductors," *Appl. Phys. Lett.,* vol. 51, pp. 1753-1755 , November 1987.

(9) R. R. Bonetti and A. E. Williams, "Preliminary Design Steps for Thin-Film Superconducting Filters," *MTT-S Digest*, pp. 273-276, May 1990.