# Quasi-Optical Millimeter-Wave Band-Pass Filters Using High-$T_c$ Superconductors

Dawei Zhang, Mehran Matloubian, *Member*, *IEEE*, Tae Wan Kim, Harold R. Fetterman, *Fellow*, *IEEE*, Kevin Chou, Shiva Prakash, C. V. Deshpandey, Rointan F. Bunshah, and Kenneth Daly

*Abstract* —**Quasi-optical millimeter-wave band-pass filters using $YBa_2Cu_3O_7$ high-$T_c$ superconducting films were fabricated on MgO and $LaAlO_3$ substrates. Transmitted power through the filter was investigated in the 75 GHz to 110 GHz frequency range at temperatures ranging from 15 to 300 K. At 15 K the measured center frequency and the bandwidth of the superconducting filter were 92 GHz and 0.85 GHz respectively. Measurements of $YBa_2Cu_3O_7$ filters were compared with similar filters fabricated using gold. At 15 K and 92 GHz, an improvement of 75% in the quality factor of the superconducting filter was obtained compared with a similar gold filter. At lower frequencies, it is expected that such superconducting filters will offer more than an order of magnitude improvement in $Q$ factor over gold filters because of the frequency-squared dependence of the surface resistance versus the gold filter, which has a frequency to the one half dependent surface resistivity. This is the first experimental observation that high-$T_c$ superconductors can be used as quasi-optical, high-performance, frequency selective surfaces.**

## I. Introduction

SINCE the discovery of high-$T_c$ superconducting materials, considerable experimental and theoretical work has been done on possible applications in microwave and millimeter-wave devices. Experimentally successful devices include ring resonators, microstrip transmission lines, and coplanar resonators [1]. Theoretical work has involved modeling high-$T_c$ mixers [2] as well as the interaction of light with high-$T_c$ striplines [3]. In this paper we report the results of experiments performed on quasi-optical millimeter-wave band-pass filters fabricated using $YBa_2Cu_3O_7$ (YBCO) superconductors. The filters consist of periodic arrays of two-dimensional crosses, and they are designed to operate in the 75–110 GHz range.

One can classify regularly spaced elements on a dielectric slab as either inductive (periodic slots) or capacitive (periodic metallization) [4]. By combining these geometries, it is possible to fabricate resonant structures. Recently, various kinds of frequency selective surface (FSS) structures, such as annular slot arrays, have been developed as band-pass filters for use in the far infrared [5]. Successful experimental [6], [7] and theoretical [8], [9] work has been done on these kinds of FSS filters, and as we show below, future work using high-$T_c$ superconducting FSS structures shows impressive potential.

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D. Zhang, M. Matloubian, T. W. Kim, and H. R. Fetterman are with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90024.

K. Chou, S. Prakash, C. V. Deshpandey, and R. F. Bunshah are with the Department of Materials Science and Engineering, University of California at Los Angeles, Los Angeles, CA 90024.

K. Daly is with TRW Inc., One Space Park, Redondo Beach, CA 90278.

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## II. Filter Fabrication

YBCO films 3000 to 5000 Å thick were synthesized using the activated reactive evaporation (ARE) process onto 1 in.$\times$1 in.$\times$0.020 in. optically polished MgO substrates [10]. During this process, copper, barium, and yttrium were evaporated from three sources, which were independently monitored to adjust the flux ratio. The yttrium source was an electron-beam-heated billet, and the copper and barium sources were resistance heated. With the introduction of oxygen gas near the substrate holder, stoichiometric YBCO films can be obtained. The secondary electrons, generated by the primary beam, form a plasma that can be controlled to enhance interactions with the film/substrate, the plasma volume chemistry, and the sources in the film growth conditions. ARE is a low-pressure ($<1$ mtorr) process that produces a YBCO film which has a mirrorlike crack-free and pore-free surface (roughness $<5$ nm). This large uniform smooth film surface is ideal for such high-frequency device applications as passive filters and resonators.

Conventional photolithographic methods were used to pattern the filters. Fig. 1 is a photograph of a patterned YBCO film taken using a scanning electron microscope (SEM). The photograph shows well-defined crosses whose dimensions are given in Fig. 2. The asymmetry of the crosses is designed to allow for tuning of the filter transmission frequency by rotating the filter crosses with respect to the polarization of the incident electric field.

## III. Experimental Results

The experimental setup is shown in Fig. 3. A computer-controlled W-band backward wave oscillator was used as the millimeter-wave source. The maximum

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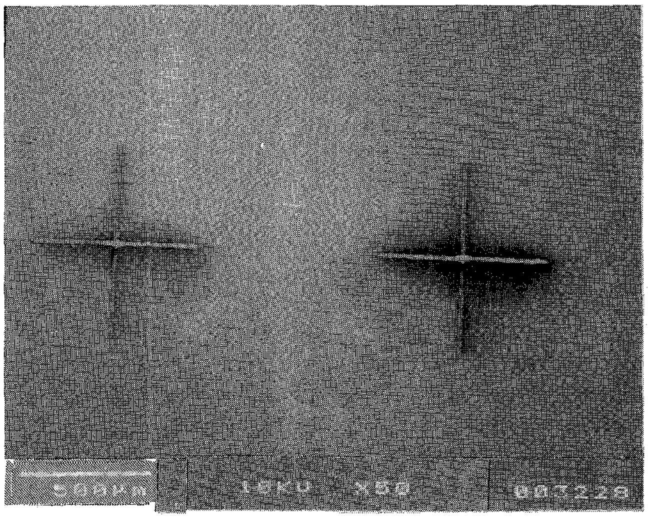
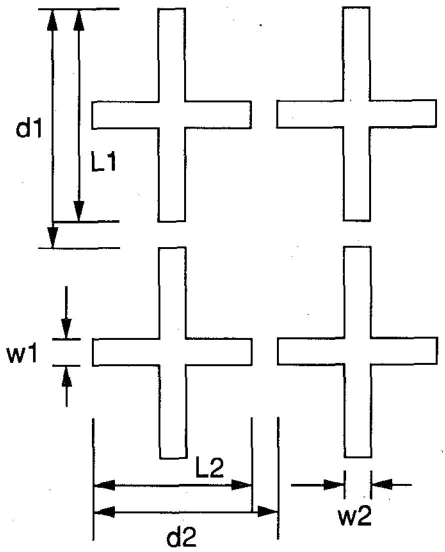


Fig. 1. Scanning electron microscope photograph of the patterned YBCO film. Cross dimensions are given in Fig. 2.




| | L(mm) | d(mm) | w(mm) |
|---|---|---|---|
| 1 | 0.713 | 1.435 | 0.020 |
| 2 | 0.617 | 1.243 | 0.020 |

Fig. 2. Dimensions of the asymmetric YBCO superconducting and gold band-pass filters.

source output power was approximately 100 mW. Linearly polarized radiation was launched from a transmitting horn on the input side of the filter and collected by a second horn located behind the filter. A thermal power meter was used to measure the power transmitted by the filter. Isolators were placed on both the input and the output side of the filter to prevent interference effects between the source and the detector. The horns and the filter were installed inside a vacuum chamber. Indium foil was used to make good thermal contact between the cold

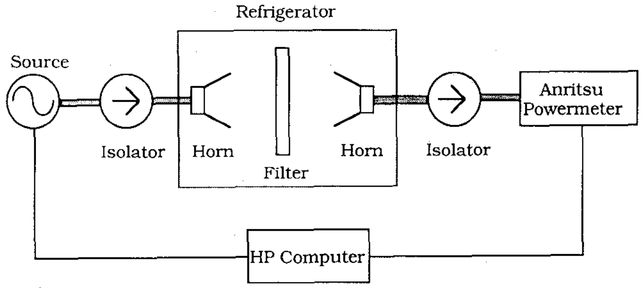


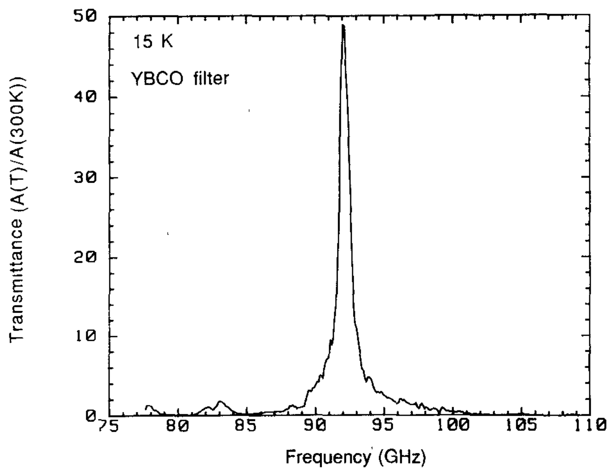

Fig. 3. Schematic diagram of the experimental setup showing the closed cycle refrigerator configuration with isolators.

finger and the filter, and a helium gas compressor was used to cool the filter. Temperature was controlled using a temperature controller with an accuracy of $\pm 0.5$ K down to 15 K.

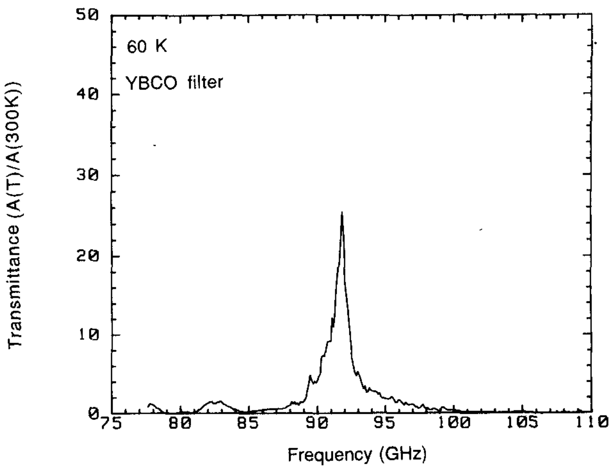
The transmitted power of a YBCO band-pass filter is shown in parts (a)–(c) of Fig. 4 at 80 K, 60 K, and 15 K respectively. Quality factors were calculated as a function of temperature. Measurement at 80 K shows a flat response, indicating that the film is a poor conductor. As the temperature is reduced, the filter $Q$ factor increases, a result which agrees well with the temperature dependence of the surface resistance. When the temperature reaches 60 K and 15 K, the quality factors become 60 and 108 respectively, indicating that the film has a lower surface resistance at lower temperatures.

From these measurements, the transmittances and resonant frequencies were also determined as a function of temperature. Fig. 5 shows a plot of the peak transmittance of the filter (normalized to the room-temperature transmission of the same superconducting filter) versus temperature. This plot shows a small change in the filter's peak transmittance at low temperatures. When the temperature was increased toward $T_c$, the transmittance dropped quickly, indicating that the losses in the film increase in the range of the transition of the superconducting material. This result agrees with a measurement of the surface resistance which shows a flat surface resistance below 60 K and a transition from 60 K to 85 K. Fig. 6 shows the filter's transmission frequency versus temperature. As the temperature was increased from 15 to 80 K, the resonant frequency of the filter shifted from 92.1 to 90.3 GHz, indicating a temperature tunability of the filter's transmission frequency over a range of 1.8 GHz. This shift in the transmission frequency shows the change of the kinetic inductance of the high-$T_c$ superconductor as a function of temperature. Filters of YBCO on $LaAlO_3$ substrates were also fabricated and tested. These filters showed a response similar to those of filters fabricated on MgO substrates; namely, as the temperature decreases below $T_c$, the quality factor becomes larger and the resonant frequency shifts to the lower side.

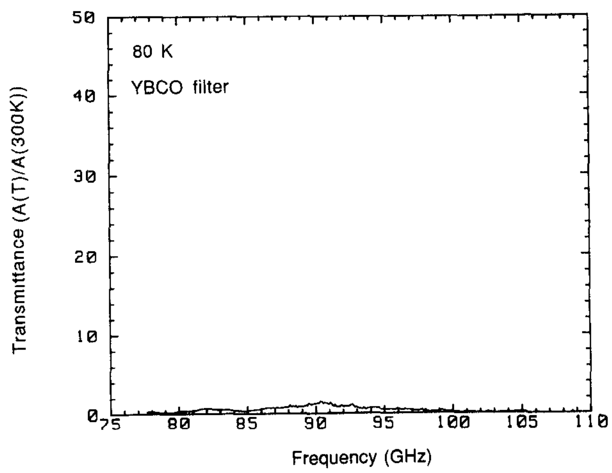
A filter using gold with a design identical to that of the YBCO superconducting filter was also fabricated and tested. Fig. 7 shows a plot of the transmitted power of the gold filter versus frequency at 15 K. Quality factors calcu-




(a)




(b)




(c)

Fig. 4. Transmittances of the YBCO filter at three different temperatures: (a) 15 K, (b) 60 K, and (c) 80 K. These transmittances are those of the YBCO filter at low temperatures normalized to the same YBCO filter at room temperature.

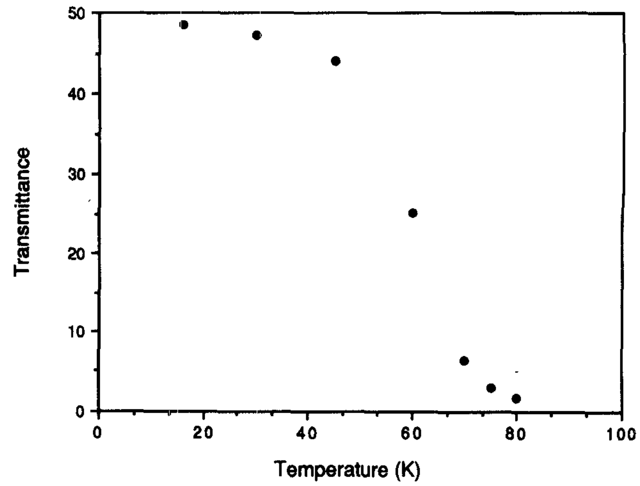



Fig. 5. Peak transmittance of the YBCO filter (normalized to room temperature) as a function of temperature. It shows a flat curve at low temperatures and a quick drop when the temperature was increased to $T_c$. This indicates a rapid increase in loss near the transition temperature of the superconducting film.

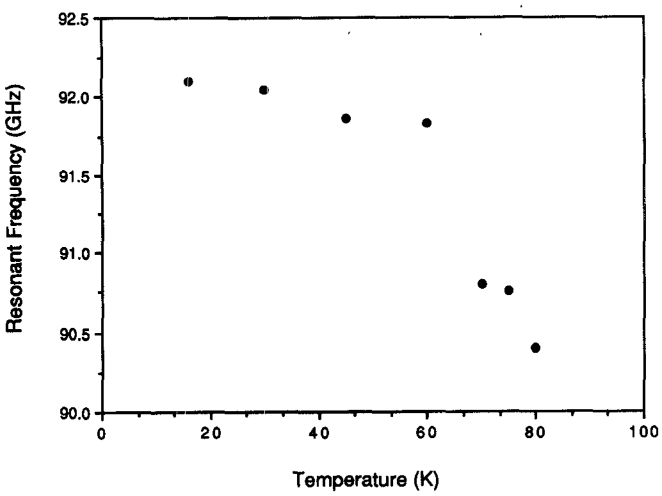



Fig. 6. Transmission frequency of the YBCO filter as a function of temperature. When the temperature was increased from 15 to 80 K, the resonant frequency of the filter shifted from 92.1 to 90.3 GHz. This follows from the decrease in the kinetic inductance of the superconductor, and results in a 1.8 GHz temperature tunability of the filter's resonant frequency.

lated from transmittance data at 15 and 300 K show only a small drop as the temperature is increased. This drop in $Q$ factor can be attributed to the temperature-dependent change in the loss tangent of the MgO substrate. In addition, no shifts of the transmission frequency were observed in the gold filter as a function of temperature. The small difference in the center transmission frequency between the YBCO filter and the gold filter was probably due to the different material etching processes in the superconductor and gold films.

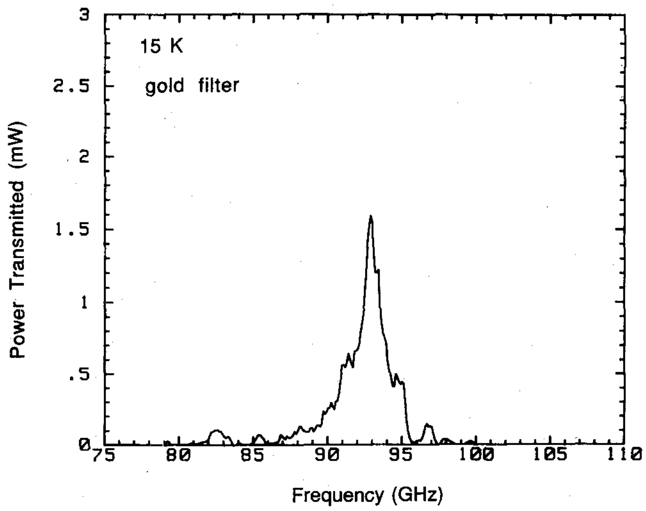



Fig. 7. Transmitted power of the gold filter, with a pattern identical to that of the YBCO superconducting filter, measured at 15 K. The full vertical scale represents the transmitted power level of the YBCO superconducting filter (3 mW) at 15 K. The gold filter shows an almost temperature independent quality factor and resonant frequency.

## IV. Discussion

A comparison of the YBCO filter characteristics with those of the gold filter reveals three pertinent temperature ranges. From 15 to 60 K, the YBCO filter has a higher $Q$, owing to a lower surface resistance; from 60 to 85 K, the gold filter has a higher $Q$, because of a lower surface resistance. From 85 to 300 K, the YBCO filter ceases to show any filtering action while the gold filter remains responsive throughout the entire temperature range. Although the YBCO filter only has a 75% higher $Q$ than the gold filter at 15 K, at least an order of magnitude improvement in $Q$ factor is expected at lower frequencies such as X band. This is due to the squared frequency dependence of the YBCO surface resistance versus the frequency to the one half dependence of the gold surface resistance.

This band-pass filter design was also theoretically modeled using a computer program [11]. In this modeling, the method of momentum and Floquet expansion techniques were used to formulate the transmission and reflection of the frequency selective surfaces. Results of the simulation were in good agreement with the experimentally observed resonances of these filters.

## V. Conclusion

We have demonstrated that YBCO superconducting thin films can be used to make effective quasi-optical millimeter-wave band-pass filters. YBCO filters are expected to have a significantly better response than similar filters fabricated using gold at low microwave frequencies. Also, the possible power limit of the YBCO thin film superconductivity may be utilized to make a filter which transmits at low powers and switches off at high powers. Future work will include exploring these possibilities as well as examining the optical response of YBCO superconducting band-pass filters [12].

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**Dawei Zhang** was born in Ningbo, People's Republic of China, on September 27, 1964. He received the B.S. degree in physics from the University of Science and Technology of China in 1987 and the M.S. degree in physics from the University of California at Los Angeles in 1988. Currently he is conducting his Ph.D. study with Prof. Harold R. Fetterman at the University of California at Los Angeles. His research interests include high-$T_c$ superconducting passive and active millimeter-wave devices and optical control of these devices.

**Mehran Matloubian** (S'86–M'89), photograph and biography not available at the time of publication.

**Tae Wan Kim**, photograph and biography not available at the time of publication.

**Harold R. Fetterman** (SM'81–F'90) received the Ph.D. degree from Cornell University in 1967.

He is currently a Professor in the Department of Electrical Engineering at the University of California, Los Angeles. He joined UCLA after 14 years at the MIT Lincoln Laboratory, where he was active in submillimeter/millimeter-wave detectors and source programs. He successfully developed heterodyne receivers and solid-state sources with applications in plasma diagnostics, remote sensing, and imaging radars. Since coming to UCLA, he has concentrated on millimeter-wave GaAs devices and the optical control and testing of high-frequency systems. Recently he has also been studying the applications of high-$T_c$ superconductors to millimeter-wave devices.

**Kevin Chou**, photograph and biography not available at the time of publication.

**Shiva Prakash**, photograph and biography not available at the time of publication.

**C. V. Deshpandey**, photograph and biography not available at the time of publication.

**Rointan F. Bunshah**, photograph and biography not available at the time of publication.

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