Application of High T_c Superconductors as Frequency Selective Surfaces: Experiment and Theory

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***Abstract*— $YBa_2Cu_3O_{7-x}$ and $Tl_2CaBa_2Cu_2O_8$ high temperature superconducting thin films were utilized to fabricate frequency selective surfaces (FSS) at millimeter-wave frequencies (75–110 GHz). An analytical/numerical model was applied, using a Floquet expansion and the Method of Moments, to analyze bandstop superconducting frequency selective surfaces. Experimental results were compared with the model, and showed a good agreement with resonant frequency prediction with an accuracy of better than 1%. The use of the superconducting frequency selective surfaces as quasi-optical millimeter-wave bandpass filters was also demonstrated.**

I. Introduction

The use of metal-mesh as a frequency selective surface has been employed by numerous researchers [1]–[6]. Recently, we demonstrated that quasi-optical millimeter-wave bandpass filters fabricated using $YBa_2Cu_3O_{7-x}$ high T_c superconductors have a superior quality factor at millimeter wave frequencies versus similar filters fabricated using gold [7]. This was due to the lower surface resistance of the high T_c superconducting thin films over conventional metals at these frequencies [8]. In this paper, we report the use and analysis of $YBa_2Cu_3O_{7-x}$ and $Tl_2CaBa_2Cu_2O_8$ high temperature superconductors as millimeter-wave frequency selective surfaces. The advantages of using superconductors as both bandpass and bandstop filters include lower insertion losses, higher Q factors [7], and optical tunability of the filter's resonant frequency [9]. In addition, because of the power limit of the superconductivity of the high T_c superconductors, a power limiter, which transmits the low power levels and stops the transmission at high powers can be developed. For these reasons, the high T_c superconductors are a much more attractive material than conventional metals in the millimeter-wave quasi-optical filter applications.

The application of superconducting FSSs at high frequencies requires an accurate theoretical analysis at millimeter-wave frequencies as well as a consideration of the conductivities of the superconductor. Since the kinetic inductance of a superconductor has a much larger contribution to the performance of a device than that of normal metals, a modeling of the resistance contribution is required in the theoretical analysis. This is accomplished by considering the unequal values of the real and imaginary parts of the surface impedance of the material. In this paper, the Method of Moments technique and the Floquet Modal expansion approach were used in a theoretical/numerical modeling of the FSSs [10]. The effects of the surface conductivity of high temperature superconductors were also added to the formulation of the model. A comparison of the experimental measurement and the theoretical simulation is discussed in the paper.

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II. Experiment

YBCO films 1000 to 5000 Å thick were synthesized using the activated reactive evaporation (ARE) process onto 1 in. × 1 in. × 0.020 in. optically polished MgO substrates. During this process, copper, barium, and yttrium were evaporated from three sources, which were independently monitored to adjust the flux ratio [12]. $Tl_2CaBa_2Cu_2O_8$ superconducting thin films were grown using a laser ablation technique, in which material from a single target of thallium, calcium, barium, and copper oxides was vaporized by a pulsed excimer laser. Noncrystalline films with thickness of approximately 1 μm were deposited at room temperature onto precleaned $LaAlO_3$ substrates. The films were then annealed by heating at approximately 860°C. Conventional photolithographic methods were used to pattern the superconducting frequency selective surfaces. Fig. 1 is a photograph of a patterned $Tl_2CaBa_2Cu_2O_8$ film taken using a scanning electron microscope (SEM). The photograph shows well-defined cross dipole structures.

The experimental setup used to measure the filters included a computer-controlled W-band backward wave oscillator as the millimeter-wave source [7]. The maximum source output power was approximately 100 mW. Linearly polarized radiation was launched from a transmitting horn on the input side of the FSS and collected by a second horn located behind the FSS. A thermal power meter was used to measure the power transmitted by the FSS. Isolators were placed on both the input and the output side of the FSS to prevent interference effects between the source and the detector. The horns and the FSS

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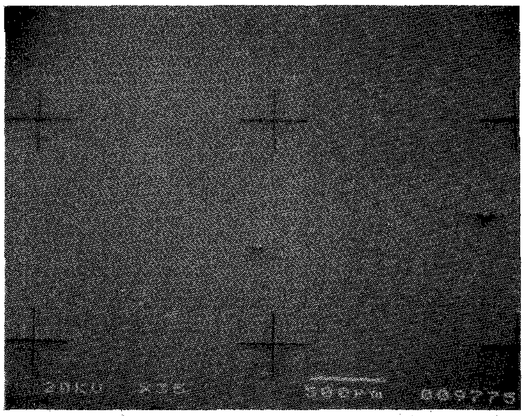

Fig. 1. Photograph of a patterned $Tl_2CaBa_2Cu_2O_8$ film from a scanning electron microscope (SEM) showing a well-defined cross dipole structure.

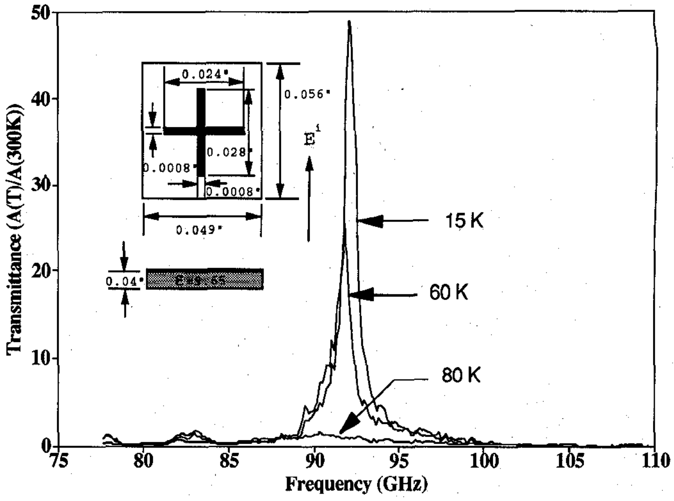

Fig. 2. Transmittances of a YBCO superconducting bandpass filter on MgO substrate at temperatures of 80 K, 60 K, and 15 K.

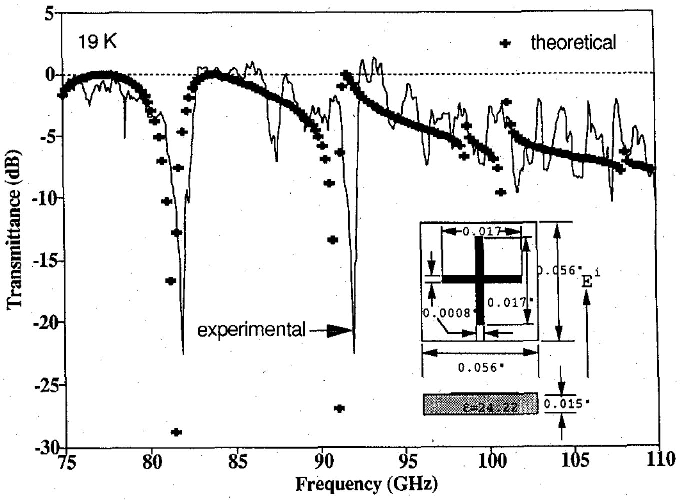

Fig. 3. Comparison of the experimental result and theoretical formulation of a $Tl_2CaBa_2Cu_2O_8$ bandstop filter showing good agreement with an accuracy of 1% in predicting the resonant frequencies.

were installed inside a vacuum chamber. Indium foil was used to make good thermal contact between the cold finger and the film, and a helium gas compressor refrigerator was used to cool the filter. Temperature was controlled using a temperature controller with an accuracy of ± 0.5 K down to 15 K.

The first application we developed utilized YBCO superconductors as millimeter wave quasi-optical bandpass filters. At temperatures far below the transition temperature (90 K) of the YBCO high T_c superconductor, the conductivity loss of the superconducting material is lower than that of a conventional metal. Thus it is expected that a higher quality factor should be obtained using a superconducting filter versus a gold filter. The normalized transmittances of a YBCO bandpass filter are shown in Fig. 2 at 80 K, 60 K, and 15 K respectively. The measurement at 80 K shows a flat response, indicating that the film is a poor conductor. As the temperature is reduced, the filter resonance gets sharper, a result which agrees well with the temperature dependence of the surface resistance. At temperatures of 60 K and 15 K, the quality factor, which is estimated from the ratio of the resonant frequency to the FWHM of the resonance, becomes 60 and 108 respectively, indicating that the film has a lower surface resistance at lower temperatures, while a gold filter with an identical pattern has a Q-factor of approximately half of that of the superconducting filter at 15 K.

Considering the cost of cooling high temperature superconductors, it is more practical to operate the millimeter wave devices at liquid nitrogen temperatures. Tl-based high temperature superconductors become attractive due to their higher T_c (101 K), which gives superior performance, at higher temperatures, than YBCO ($T_c = 90$ K). A new bandstop filter pattern was designed on 15 mill $LaAlO_3$ substrates for the $Tl_2CaBa_2Cu_2O_8$ high temperature superconductors. A 1" × 1" bandstop filter was fabricated, and Fig. 3 shows the transmittance of the bandstop filter as a function of frequency at 19 K. Two resonant peaks were observed at 82 and 92 GHz. As the temperature increases, both peaks shifted to lower frequencies, with a maximum shift of 0.6 GHz over the range from 18 K to 100 K, a result which agrees with the drop of the kinetic inductance of the superconducting material. At a higher temperature of 77 K, the $Tl_2CaBa_2Cu_2O_8$ bandstop filter still gives a good filtering response compared to that at 18 K, while a similar measurement of a YBCO/MgO bandstop filter shows a large decrease in the filter performance over the range of 18 K to 77 K. This is consistent with surface resistance measurements made using cavity techniques. A full comparison between experiment and theory is discussed in the next section of the paper.

III. Theoretical and Computer Models

The Methodology of the theoretical formulation and computer program models are summarized in this section. This formulation which can include substrate effects uses the modal analysis approach. The FSS is assumed to be flat and infinite in extent. The methodology of the implementation is shown in Fig. 4 and it is based on the approach developed in [10], [11]. First, by assuming that the structure is periodic a representative cell can be defined. Second, the configuration of the conductive element in the cell is broken into many

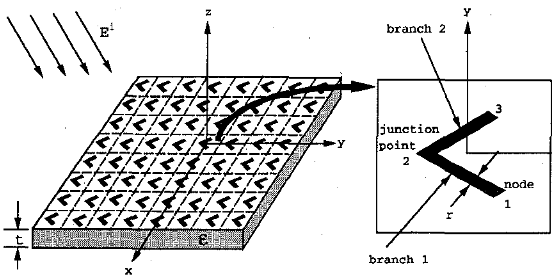

Fig. 4. Geometry of a generalized FSS configuration showing segmentation used in MOM.

linear segments by identifying the node points for the initial and the end points of the linear segment (see branches in Fig. 4). This linear segmentation allows one to utilize complex shapes for the conductive element, such as, dipole, Jerusalem cross, rectangular loops, etc. If there is an intersect on contact point, the same node point at the contact is used for all the branches intersecting at this point and making electrical contact there. Third, each linear segment is then divided into several subdivisions in order to define the current basis function for the implementation of the method of moments (MOM). Fourth, the method of moments formulation is then constructed utilizing the Floquet expansion technique in conjunction with the boundary condition that the total tangential electric field be zero on the perfectly conducting conductive element. Additionally, in order to make the formulation of the problem more complete and realistic, the effects of the surface conductivity have been added to the formulation by modifying the appropriate terms of the matrix equation. The direction and polarization of the incident plane wave can also be varied in this formulation. The output of the computer program are the induced currents, reflection and transmission coefficients. As it is well-known for these types of problems, considerable amount of attention must be given in the selection of the number of Floquet modes and current basis functions. Typically, the convergence of the results are verified by performing appropriate numerical tests which vary the number of modes and basis functions. Some representative results will be shown in the next section. Even though the results shown in this paper are for bandstop structure, with appropriate modifications the analytical/numerical model can also be used for bandpass structure.

IV. Results and Discussions

The computer program is first tested by calculating the TM-mode transmission of a single dipole structure. Since for the TM-mode, the free space wavelength at 90 GHz is 150 times longer than the width of the single dipole, it is expected that the transmitting millimeter waves will not be appreciably affected by the dipole structure. Therefore, the transmittance of such dipole structure for the TM polarization should be that of a blank substrate. Fig. 5 shows the comparison of the computer program output using 96 Floquet modes and 16 triangle current basis functions with an analytical result calculated for the blank substrate. The plot shows excellent agreement between

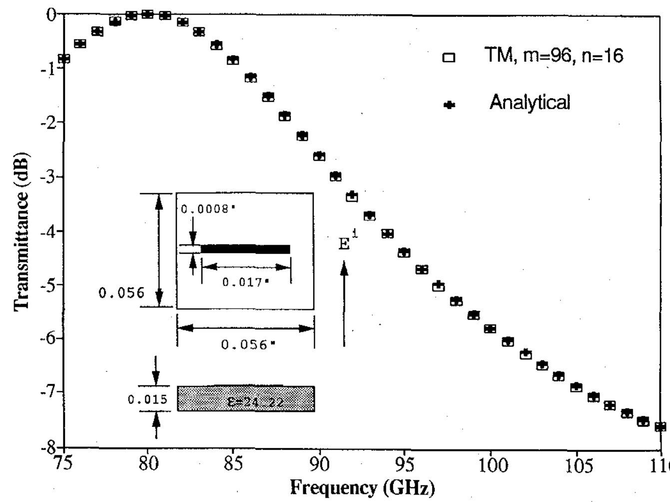

Fig. 5. Comparison of the program output with an analytical result calculated for a blank substrate. The plot shows a good agreement between the program and the analytical calculation.

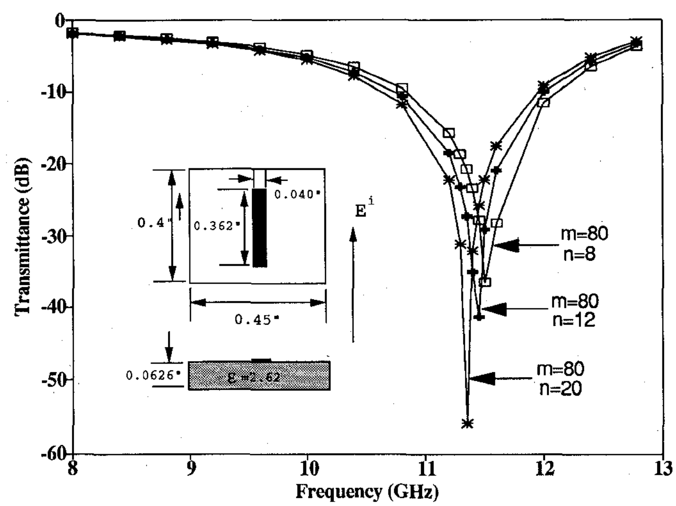

Fig. 6. Convergence test for a single dipole structure showing the effects of increasing the number of triangle current basis functions.

the computer program results and the analytical calculations. As expected, when the substrate thickness is half of the substrate wavelength no transmission loss is predicted.

To further investigate the convergence properties of the formulation, a comparative study has been performed by trying to repeat the results presented in [13]. The geometry of this FSS is shown in Fig. 6. Many convergence tests were performed. As an example, the number of the Floquet modes were fixed at 80 and the number of the triangle current basis functions were changed from 8, to 12, and then to 20. From Fig. 6, one observes that the resonant frequency of the transmittance shifts to the lower values as the number of triangle current basis functions are increased. The converged result agrees well with the one presented in [13]. Detailed convergence studies have revealed that typically more current basis functions are required near the resonant length of the conducting element. This is because in this generalized

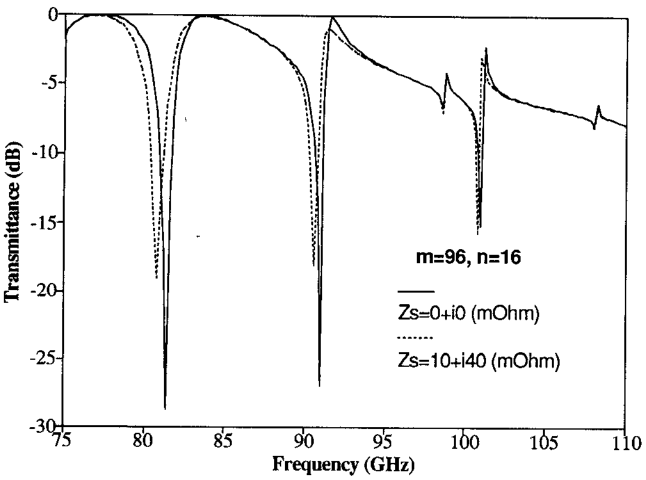

Fig. 7. Comparison of the zero impedance and finite impedance. The impedance of the material caused a shift in resonant frequency to a lower value and a drop in Q factor.

formulation subdomain basis functions were used instead of entire domain basis functions. Also, it has become clear that a larger order of Floquet modes are necessary as the ratio between the cell size and the width of the conducting element becomes larger. Finally, as the thickness of the substrate becomes larger in terms of the substrate wavelength (more than of approximately 1/10 of the substrate wavelength) the resonance frequency is shifted from the free space resonant frequency to the resonant frequency based on the averaged permittivity of the substrate and the air.

The effects of the finite conductivity of the conducting element has also been investigated. Fig. 7 shows a comparison of the computer program output for an FSS configuration depicted in Fig. 3 by varying the surface impedance of the element. The value of the surface impendance, which was reasonably chosen from the typically measured values of the high T_c superconducting thin films at the corresponding frequency, to be $Z_s = 10 + j40$ mOhm. This arbitrary choice of the Z_s will in no way affect the validity of the modeling, which intends to show the qualitative effect of the Z_s on the FSS structures. It is clear that for the case of non-zero impedance, the quality factor of the resonance is dropped due to the resistive loss of the material and the resonance is shifted to the lower value in frequency due to the contribution of the kinetic inductance of the material. This prediction agrees with experimentally observed shift of the resonant frequencies and drop of Q-factors of the superconducting bandstop filter measured in Fig. 3.

Finally, the results of the theoretical formulation and computer program is compared with experimental results of a bandstop FSS structure on $LaAlO_3$ substrate shown in Fig. 3. A 1" × 1" × 0.015" $LaAlO_3$ substrate was used with a measured dielectric constant of 24.22. An FSS configuration was designed with $L1 = L2 = 0.017"$, $d1 = d2 = 0.113"$, and $w1 = w2 = 0.787 \times 10^{-3}"$ (see [7] for details). As evident from Fig. 7, the results of the numerical simulation agrees with an accuracy of better than 1% with the experimental data in predicting the resonant frequencies in the range of 75 to 110 GHz.

V. Conclusion

In conclusion, we have demonstrated that YBCO and Tl-based superconducting thin films can be used to make high performance frequency selective surface structures at millimeter-wave frequencies. The comparison between experiment and theory showed good agreement. In the future, analytical/numerical modeling of the high T_c superconducting frequency selective surface structures could potentially provide an alternative approach for deriving the temperature dependence of some fundamental parameters of high T_c superconductors, such as surface resistance, and the real and imaginary parts of the conductivity. A full characterization of Tl-based superconducting bandpass filters, which yield a higher performance in Q factors at 77 K over YBCO filters, is being investigated, and will be reported later.

Acknowledgment

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References

[1] R. Ulrich, "Far-infrared properties of metallic mesh and its complementary structures," *Infrared Physics,* vol. 7, pp. 37–55, Mar. 1967.

[2] R. C. Compton, R. C. McPhedran, G. H. Derrick, and L. C. Botten, "Diffraction properties of a bandpass grid," *Infrared Physics,* vol. 23, no. 5, pp. 239–245, Jan. 1983.

[3] A. Roberts and R. C. McPhedran, "Bandpass grids with annular apertures," *IEEE Trans. Antennas Propagat.,* vol. 36, no. 5, pp. 607–611, May 1988.

[4] P. A. Krug, D. H. Dawes, and R. C. McPhedran, W. Wright, J. C. Macfarlane, and L. B. Whitbourn, "Annular-slot arrays as far-infrared bandpass filters," *Optics Letters,* vol. 14, no. 17, pp. 931–933, Sept. 1989.

[5] V. P. Tomaselli, D. C. Edewaard, P. Gillan, and K. D. Moller, "Far-infrared bandpass filters from cross-shaped grids," *Applied Optics,* vol. 20, no. 8, pp. 1361–1365, Apr. 1981.

[6] C. M. Rhoads, E. D. Damon, and B. A. Munk, "Mid-infrared filters using conducting elements," *Applied Optics,* vol. 21, no. 15, pp. 2814–2816, Aug. 1982.

[7] D. Zhang, M. Matloubian, T. W. Kim, H. R. Fetterman, K. Chou, S. Prakash, C. V. Deshpandey, R. F. Bunshah, and K. Daly, "Quasi-optical millimeter-wave bandpass filters using high T_c superconductors," *IEEE Trans. Microwave Theory Tech.,* vol. 39, no. 9, pp. 1493–1497, Sept. 1991.

[8] J. P. Carini, A. M. Awashi, W. Beyermann, G. Gruner, T. Hylton, K. Char, M. R. Beaseley, and A. Kapitulnik, "Millimeter-wave surface resistance measurements in highly oriented $YBa_2Cu_3O_{7-\delta}$thin films," *Phys. Rev. B,* vol. 37, pp. 9726–9729, June 1988.

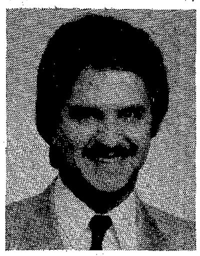
[9] D. Zhang, D. V. Plant, H. R. Fetterman, K. Chou, S. Prakash, C. V. Deshpandey, R. F. Bunshah, "Optical control of millimeter-wave high T_c superconducting quasi-optical bandpass filters," *Appl. Phys. Lett.,* vol. 58, no. 14, pp. 1560–1562, Apr. 1991.

[10] Y. Rahmat-Samii, W. Imbriale and V. Galindo, "Reflector antennas with mesh surfaces: Contact or no contact at wire intersections?," *AP-S Int. Symp.,* San Jose, CA, vol. 1, June 1989, pp. 258–261.

[11] W. A. Imbriale, V. Galindo, and Y. Rahmat-Samii, "On the reflectivity of complex mesh surface," *IEEE Trans. Antennas Propagat.,* vol. 39, pp. 1352–1365, Sept. 1991.

[12] S. Prakash, D. M. Umarjee, H. J. Doerr, C. V. Deshpandey, and R. F. Bunshah, "Superconducting films grown *in situ* by the activated reactive evaporation process," *App. Phys. Lett.,* vol. 55, no. 5, pp. 504–506, July 1989.

[13] F. S. Johnson, "Convergence phenomenon in the solution of dichroic scattering problems by Galerkin's method," *Proc. Inst. Elec. Eng.,* vol. 134, pt. H, no. 1, pp. 87–92, Feb. 1987.



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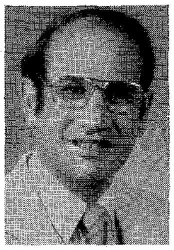

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S. Prakash, photograph and biography not available at the time of publication.

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