Superconducting Millimeter-Wave *E*-Plane Filters

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Abstract—**In this paper, we report the measured performance of a three-pole *E*-plane filter constructed from high-T_c superconducting bulk materials at 34.5 GHz. Experimental results are presented for the insertion loss and return loss of the filter at 77 K. The problems associated with the use of bulk materials at the millimeter-wave range are addressed. Other possible superconducting waveguide filter configurations are proposed. While the experimental results are taken at low input power level, the current distribution inside the filter structure is calculated, and the power handling capability of the superconducting filter is discussed.**

I. Introduction

Over the past four years, a considerable number of papers have been published to demonstrate the feasibility of using high-T_c superconductor bulk material in microwave applications. However, in most of these papers, only single cavities were considered and the emphasis was on measuring the microwave characteristics of the superconducting materials. Despite the fact that the current bulk material is coarse and porous by microwave standards, the measured results reported in [1]–[4] show that high-T_c superconductor bulk materials do exhibit low loss at microwave frequencies for temperatures well below the transition point.

Various fabrication processes have recently emerged for high-T_c superconductor thick film coating, and progress toward the development of bulk microwave components is proceeding rapidly. It has been reported [5], [6] that a number of bulk microwave cavities at 5 GHz and 10 GHz may be included in the High Temperature Superconductivity Space Experiment (HTSSE-I) of the Naval Research Laboratory.

Owing to the difficulty of using screws to tune superconducting filters at liquid nitrogen temperatures, the structure of a superconducting filter must lend itself to rigorous computer-aided modeling. The *E*-plane filter structures shown in Fig. 1 combine the advantages of ease of manufacturing and suitability for CAD design. With the development of more advanced fabrication techniques for bulk materials and thick film coating, this type of filter is an attractive candidate for constructing high-T_c superconducting waveguide filters.

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In satellite output multiplexer applications, the requirements of extremely low loss and high power handling capability preclude the use of superconducting thin-film filters. As the critical current density of the high-T_c thick films is improved, superconducting waveguide filters can be potentially employed in such applications. By replacing the silver-plated cavity walls by superconducting walls, unloaded Q values of more than 100 000 are expected at Ku band. The use of filters with such high Q values in output multiplexers translates into higher transmitted power, which in turn results in improvement of the satellite EIRP.

In this paper, we report the measured results of an experiment to construct a millimeter-wave *E*-plane filter from high-T_c superconductor bulk materials. Although the results obtained confirm that bulk materials are not yet useful for millimeter-wave applications, a wealth of important information can be derived from this experiment.

With the use of the mode matching technique, we also calculate in this paper the field distribution inside the filter structure. The currents flowing on the input section of the filter are presented in the passband and the stopband. The effect of the critical current density on the power handling capability of the superconducting filter is investigated.

II. Filter Configuration

E-plane filters have been widely used in many microwave and millimeter-wave applications, demonstrating an excellent performance up to 100 GHz. The filter consists of a ladder-shaped insert placed at the center of a rectangular waveguide. The insert can be of pure metal or can be printed on a dielectric substrate. A rigorous field theory analysis has been presented for this type of filter in [7] and [8], where it is shown that the theoretical results agree well with the measured data.

Fig. 1 shows two possible configurations for superconducting *E*-plane filters. The waveguide housing is made of high-T_c superconducting material which can be realized either by using bulk material or thick film coating. In Fig. 1(a) the insert is a pure metal, while in Fig. 1(b) the insert is made of high-T_c superconductor thin films printed on a substrate with a relatively low dielectric constant, such as magnesium oxides. Although the dielectric sub-

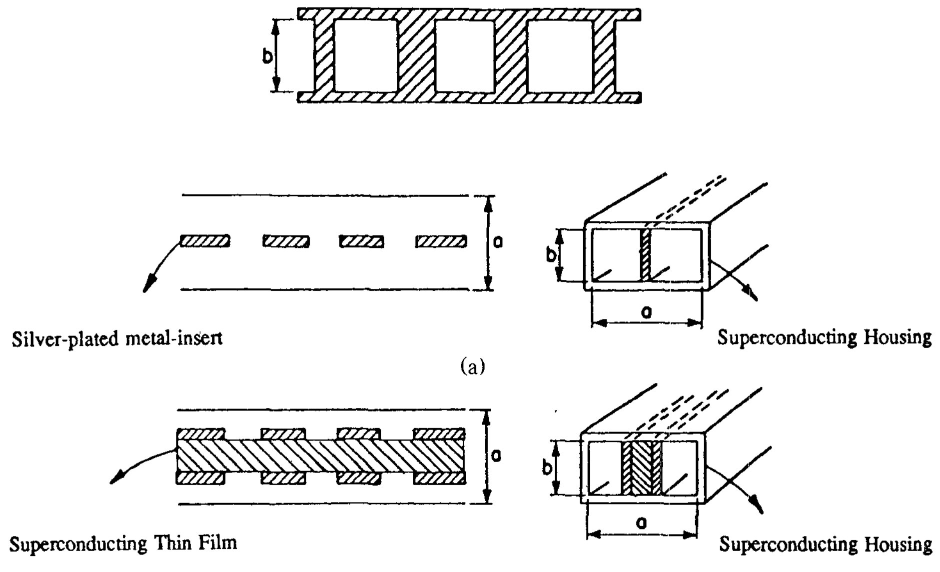


Fig. 1. Two possible configurations for superconducting E-plane filters.

strate causes additional losses, the configuration given in Fig. 1(b) offers miniature size and facilitates integration with other microwave integrated circuit components.

Several factors, such as bandwidth and the order of the filter, affect the ratio of the power dissipated in the waveguide housing to that dissipated in the insert. However, as will be shown in Section III, the insertion loss of metal-insert E-plane filters is dominated by the power dissipated in the waveguide housing.

Fig. 2 illustrates the superconducting E-plane filter configuration constructed for the present experiment. A groove is machined in a block of superconducting YBCO bulk material (courtesy of McMaster University) using a well-controlled grinding machine. Two of the YBCO U-shaped blocks are then inserted in two silver-plated waveguide halves. The two waveguide halves and a silver-plated metal insert are bolted together to form a three-pole E-plane filter with a superconducting housing. The filter is built with WR-28 waveguide flange and is designed to operate at a center frequency of approximately 34.5 GHz. The insert has been fabricated by photoetching with a thickness of 0.003 in. The overall length of the filter is close to 0.9 in. The details of the filter dimensions are given in Fig. 3.

The outside dimensions of the U-shaped YBCO blocks and the inside dimensions of the metallic housing have been adjusted to compensate for incompatibility of the thermal expansion coefficients. In the case of a TE_{10} incident mode, only TE_{n0} modes will be excited in the filter structure. Since for these modes, the transverse component of the current is zero at the waveguide center, the joint between the superconducting blocks and the insert has a negligible effect on the filter insertion loss.

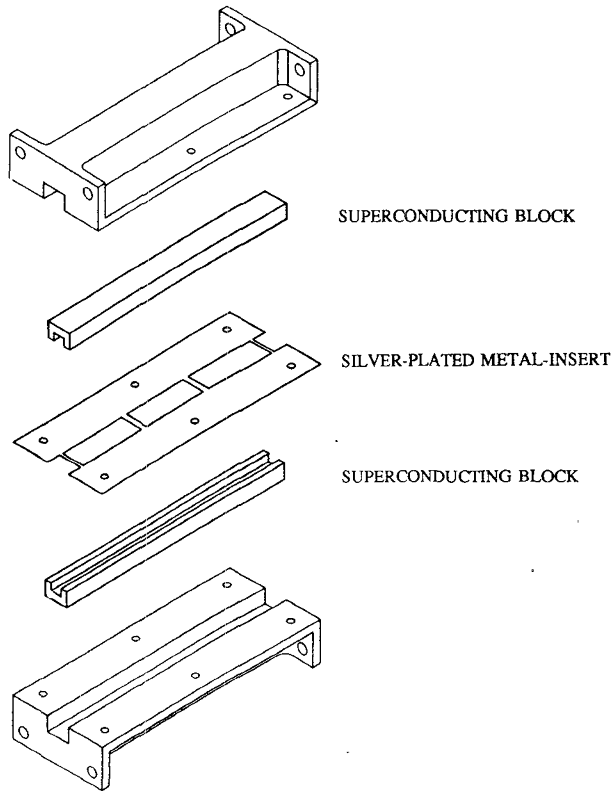


Fig. 2. The E-plane filter configuration constructed for the present experiment.

III. Experimental Results

The performance of a fully silver plated filter was first measured using two U-shaped silver-plated metal blocks in place of the two U-shaped YBCO blocks. Fig. 4 shows the measured isolation characteristics of the filter. The insertion loss observed over a return loss bandwidth of 25 dB was 0.3 dB, which corresponds to an effective unloaded Q of approximately 3000. In order to determine the relation between the power dissipated in the housing and that dissipated in the insert, the same filter was measured with brass and gold-plated metal inserts. Table I gives the insertion loss observed with various insert

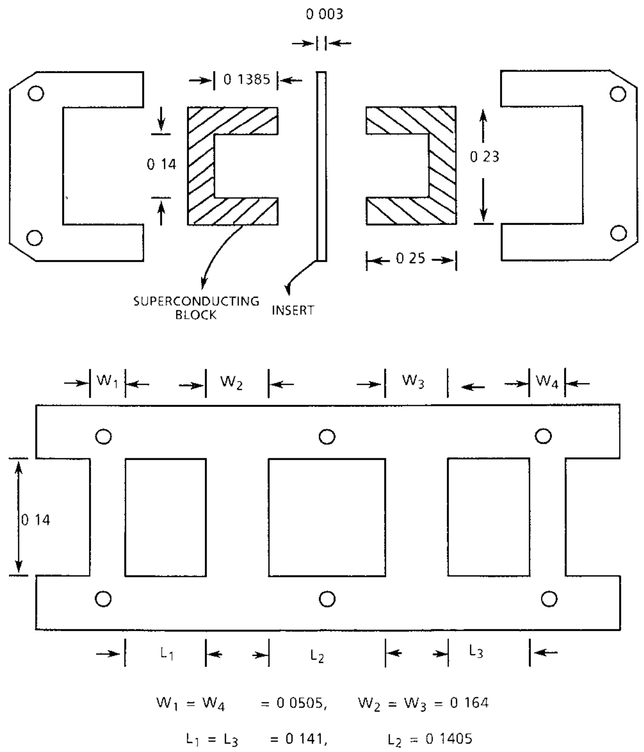


Fig. 3. Details of the filter dimensions.

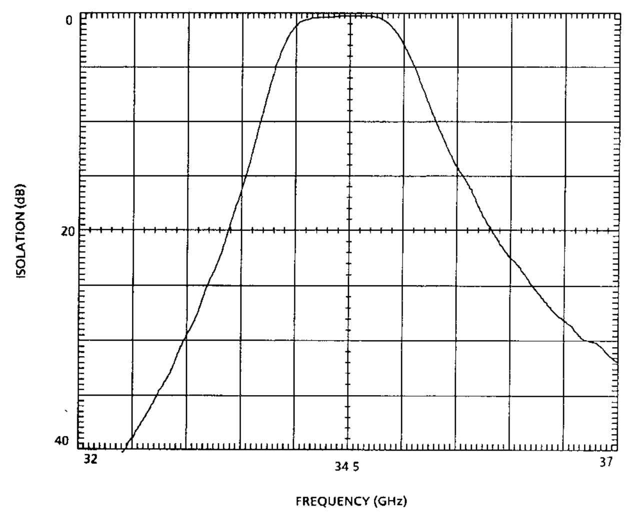


Fig. 4. The measured isolation characteristics of a fully silver plated filter structure.

TABLE I
THE MEASURED INSERTION LOSS OF A METAL INSERT E-PLANE FILTER FOR VARIOUS INSERT TYPES

Insert Type	Insertion Loss in (dB)
Silver-plated	0.3
Gold-plated	0.41
Brass	0.42

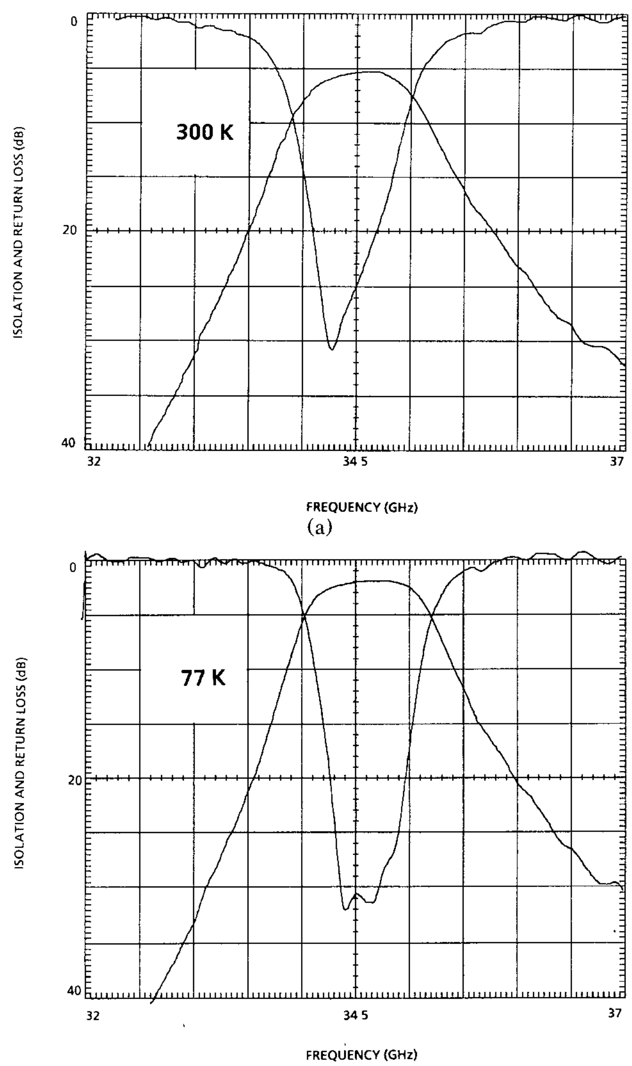


Fig. 5. The measured isolation and return loss characteristics of the superconducting E-plane filter. (a) $T = 300$ K; (b) $T = 77$ K.

types. It can be readily seen that the insertion loss of the filter is mainly determined by the power dissipated in the waveguide housing.

With the two U-shaped YBCO blocks inserted into the housing, and with the use of a silver-plated metal insert, the filter was sealed and cooled to 77 K in a liquid nitrogen cryostat. Fig. 5 shows the measured isolation and return loss performance of the superconducting filter at 300 K and 77 K. The insertion losses measured at 300 K and 77 K were 5.5 dB and 1.8 dB respectively.

The poor performance observed in this experiment is attributed to the surface damage caused by machining. Although the YBCO material was reannealed after machining, the surface roughness was still quite high relative to the wavelength at 34.5 GHz. Fig. 6 shows the machined surface of the U-shaped YBCO blocks under 200 times magnification. It is observed that the machined surface of the blocks was neither fully nor uniformly superconductive.

The high insertion loss obtained is also attributed to the quadratic loss–frequency dependence of the YBCO sample used. At the time this experiment was performed, most of the available high-T_c bulk materials were in a small disk form, which only allowed the construction of

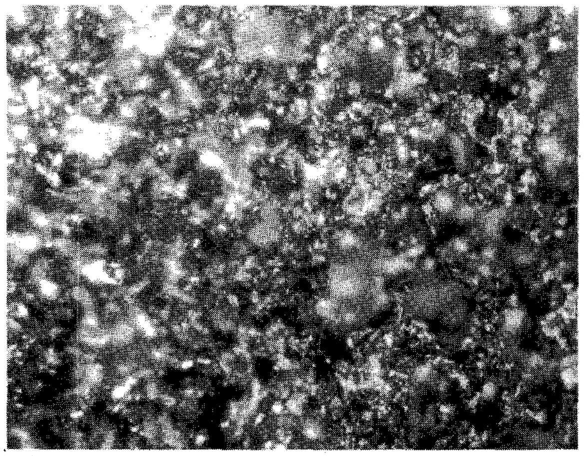


Fig. 6. The machined surface of the U-shaped YBCO blocks under 200 times magnification.

filters in the millimeter-wave range. The use of thick film coating to construct superconductive E-plane waveguide filters at a lower frequency range is currently under investigation.

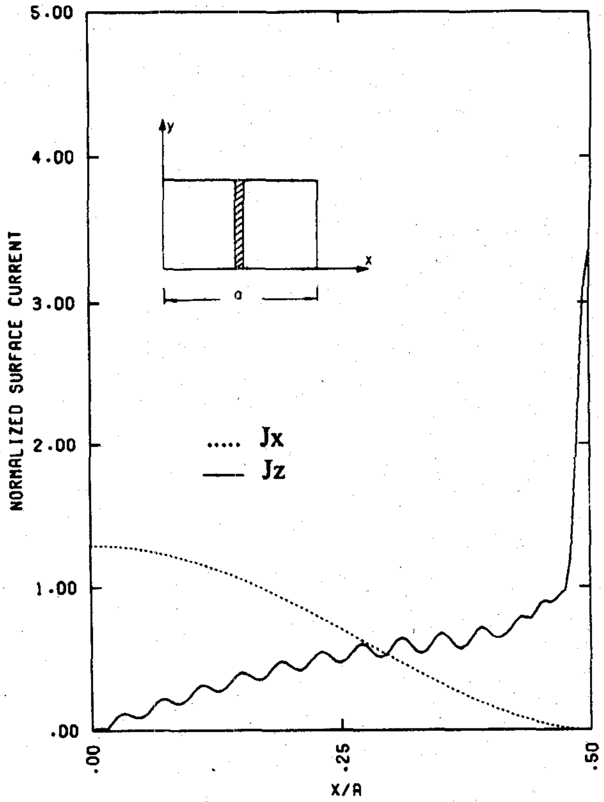
IV. Power Handling Capability

The low value of the critical current density of the superconducting material limits the power handling capability of the filter and eliminates some of the most promising applications. With a knowledge of the field distribution inside the filter structure and the value of the critical current density, the power handling capability of the superconducting filter can be predicted.

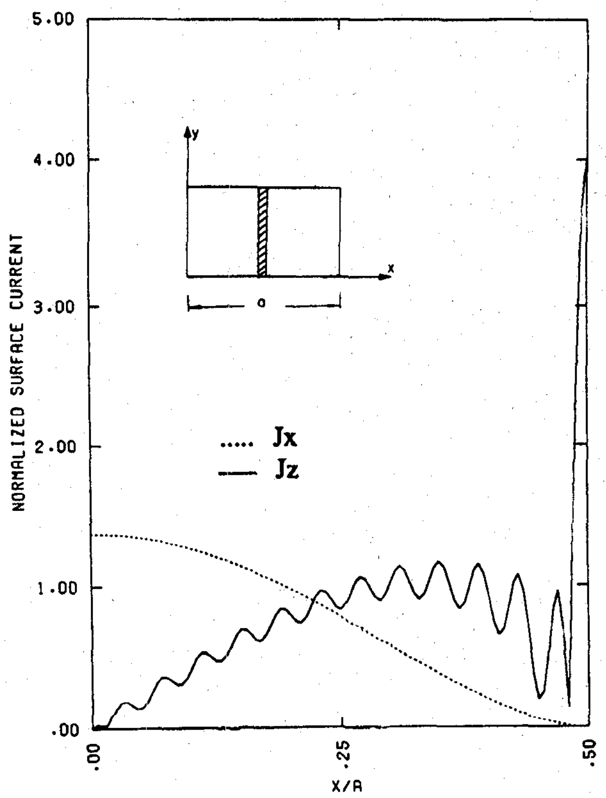
Although numerous papers have been published on the analysis and design of E-plane filters, no accurate description has been reported for the field configuration. In this paper, the mode matching formulation presented in [7] and [8] is extended to calculate the field distribution inside the filter structure.

Having calculated the tangential components of the magnetic field H_x and H_z, the surface current can be readily determined. Fig. 7 shows the two components of the surface current J_z and J_x computed at the plane of the filter input using 20 modes. In Fig. 7(a) the current is calculated at a frequency within the passband, while in Fig. 7(b) it is computed in the stopband. The current components are normalized with the assumption that the input power of the incident mode is the same for the passband and the stopband. Typically, filters are designed to meet specific rejection requirements in the stopband, and in many applications (e.g. diplexers and multiplexers) the input power in the stopband is equal to that in the passband.

In view of Fig. 7, it is observed that the surface current flowing on the input section of the waveguide in the stopband is larger than that in the passband. Within the stopband, only the input section of the filter is of concern. However, the filter may not meet the rejection requirements if the surface current density in this section far exceeds the critical value and the superconductor mate-



(a)



(b)

Fig. 7. The field components at the plane of the filter input. (a) passband; (b) stopband.

rial fails to remain superconducting. Moreover, the stopband current generated in the input section may be large enough to cause heating, which in turn may create thermal runaway and drive the complete filter to the nonsuperconducting state. Thus, not only the passband but also the stopband should be considered in evaluating the power handling capability of the superconducting waveguide filter.

V. Conclusions

Measurements of the insertion loss and return loss of a superconducting E-plane filter at liquid nitrogen temperatures have been presented. The performance achieved in this experiment confirms that the current bulk material is not yet capable of being used in millimeter-wave applications. However, with the material characteristics improved, this experiment demonstrates the feasibility of building simple superconducting waveguide filter structures with no adjustable tuning elements. Investigation of the current flowing on the input section of the filter has shown that in examining the power handling capability of the filter, the full band of operation should be considered to ensure that the superconductor housing remains superconducting within the passband as well as the stopband. It is expected that a much better loss performance will be achieved with the use of thick film coating for the waveguide housing and the metal insert.

References

[1] E. Belohoubek, A. Fathy and D. Kalokitis, "Microwave characteristics of bulk high-T_c superconductors," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1988, pp. 445–447.

[2] T. M. P. Percival, J. S. Thorn, and R. Driver, "Measurements of high-T_c superconductivity in a microwave cavity," *Electron. Lett.*, vol. 23, pp. 1225–1226, 1987.

[3] J. R. Delayen *et al.*, "RF properties of an oxide-superconductor half-wave resonant line," *Appl. Phys. Lett.*, vol. 52, pp. 930–932, Mar. 1988.

[4] K. Aida and T. Ono, "Microwave surface resistance measurement technique for cylindrical high-T_c superconductor," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1989, pp. 559–562.

[5] M. Nisenoff, "Space applications of microwave superconductors," presented at IEEE MTT Workshop on Superconducting Microwave Applications, May 1990.

[6] M. Nisenoff, D. U. Gubser, S. A. Wolf, J. C. Ritter, and G. Price, "High temperature superconductivity space experiment (HTSSE): passive millimeter-wave devices," to be published.

[7] R. R. Mansour and R. H. MacPhie, "An improved transmission matrix formulation of cascaded discontinuities and its application to E-plane circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1490–1498, Dec. 1986.

[8] R. R. Mansour, R. S. K. Tong, and R. H. MacPhie, "Simplified description of the field distribution in finlines and ridge waveguides and its application to the analysis of E-plane discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1825–1832, Dec. 1988.

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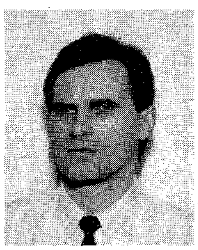

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