HIGH TEMPERATURE SUPERCONDUCTOR MICROWAVE FILTERS FOR SATELLITE TECHNOLOGY

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ABSTRACT

High temperature superconducting (HTS) microwave filters have potential to improve the performance of communication satellites. The motivation for developing HTS filters for commercial space craft is discussed. Then, some of the progress in fabrication of microstrip filters is described. This includes ion beam milling and contact formation.

INTRODUCTION

The discovery of high temperature superconductors (HTS) with critical temperatures above 77 K has opened the possibility of new applications of superconductivity. The low surface resistance of HTS thin films raises the possibility of using HTS microwave filters on communication satellites. The work described here is on developing microstrip devices which are fabricated from HTS thin films. In the present state of the art, the HTS thin films are either $YBa_2Cu_3O_7$ (YBCO) or $Tl_2Ba_2CaCu_2O_8$ (TBCCO). The films are grown epitaxially on $LaAlO_3$ substrates. There are a number of problems which must be solved in order to make the use of HTS microwave filters practical. The first part of this paper will discuss communication satellite systems and the requirements for possible HTS applications. The development of devices must be made with the improvement of the entire system in mind. The second part describes progress being made in the fabrication of devices by work in a collaboration between NRC and Com Dev.

SATELLITE SYSTEMS

The primary drivers in the design of satellite systems are costs and performance enhancements. Engineers are pushed towards miniaturization of equipment and reduction in power consumption. The high temperature superconductor technology has the potential of meeting these objectives and at the same time could provide performance not available with other technologies.

Figure 1 illustrates a block diagram of a satellite payload. It consists of receive and transmit antennas, Low Noise Amplifier (LNA) and downconverter, input and output multiplexers (Mux) and high power amplifiers. The LNA and the downconverter are generally designed as a single cascaded unit referred to as the receiver.

The input and output multiplexers comprise a substantial portion of the payload and are considered *a true* stumbling block in radical miniaturization of satellite payloads. The types of filter designs that have been employed over the past three decades for C-band (3.90 Ghz to 6.20 Ghz) satellite multiplexer applications are: i) High-order standard single-mode waveguide Chebyshev filters (1971-1982), ii) Dual-mode quasi-elliptic waveguide filters (1978-1989), and dual-mode quasi-elliptic dielectric resonator (DR) filters (1983-present).

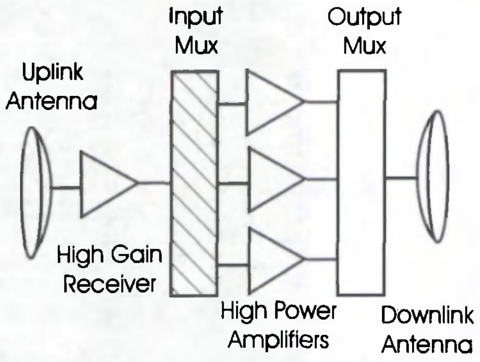

Fig. 1 A simplified block diagram of satellite payloads.

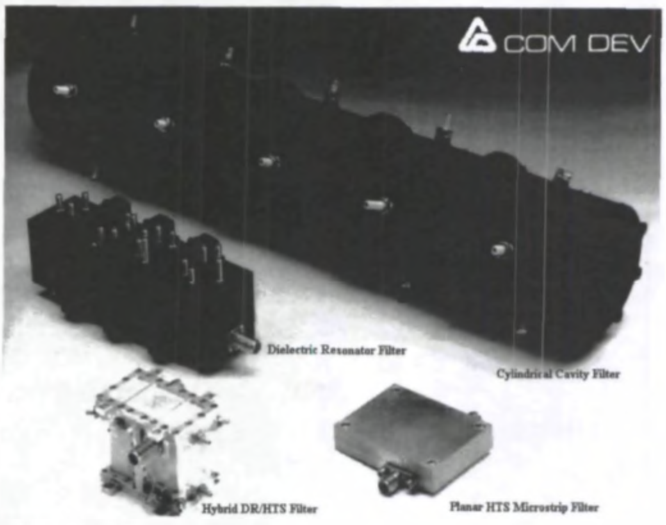

Fig. 2 A comparison of the relative sizes of C-band input channel filters realized using waveguide technology, dielectric resonator technology, and superconductor technology.

Figure 2 is a pictorial comparison between C-band input channel filters realized using waveguide technology, dielectric resonator technology and superconductor technology. Two types of superconductive filters are included in this Figure: one uses the hybrid DR/HTS technology and the other is based on HTS microstrip technology. A significant reduction in size and mass can be achieved with the use of HTS technology. The fundamental basis for this size reduction is the extremely low losses of HTS thin films at microwave frequencies. The low losses permit increasing the dielectric constant of microstrip resonators, something that cannot be done using normal metals. Since wavelength decreases as the square root of the dielectric constant, smaller filters result. In addition to just changing the dielectric constant, it is possible to use propagation modes such as quasi-TEM that have never been used for high performance filters because metal losses with these modes are too high.

The importance of the size reduction is apparent when considering that a modern satellite uses 60 input channel filters. Owing to the large number of channel filters, any reduction in filter mass and volume can lead to greater communication capacity and/or increased lifetime, thus reducing the cost of a satellite channel. A more detailed comparison between superconductive technology and conventional technology for input multiplexers is given in [1], [2]. The following points outline the major design issues for the *realization* of HTS multiplexers for satellite applications.

Defects in HTS films and substrates

The performance of highly selective narrow band filters is quite susceptible to even minor defects in HTS films and substrates. It can be readily shown that a manufacturing defect or an inherent local defect in the HTS thin film that is in the range of 2 to 3 μm may cause about a1 MHz deviation in the resonance frequency of a C-band HTS thin film resonator. Similarly, nonuniformities in substrates such as a difference in dielectric constant between 23.5 and 24 can cause a shift of 40 MHz. The specifications of the present generation of satellite systems require that the center frequency of RF channels are held to within ± 300 kHz. As a consequence, a shift of 1 MHz in the filter center frequency would be unacceptable to the commercial satellite industry.

Thermal stability of the HTS filters

HTS channel filters must be stable to thermal cycling to ensure performance repeatability as the temperature changes from cryogenic (testing) to room temperature (storage) and then back tocryogenic (operation). As mentioned earlier the center frequency of C-band input channel filters are typically maintained to within ± 300 kHz. The extreme temperature changes that the filter is exposed to, may cause a noticeable performance deviation.

High power handling capability

The microwave power dependence of the superconducting HTS films limits the power handling capability of superconducting filters and eliminates some of the most promising applications. Q-degradation and non-linearities in superconducting thin film filters have been observed at relatively low input power levels. This non-linearity may in turn lead to the generation of passive intermodulation (PIM) products [3],[4].

The operating power of input and output multiplexers can vary from one satellite to another. Typically, input multiplexers operate at very low power levels (milliwatts), while output multiplexers operate at 10-120 watts per channel filter. More recently, the feasibility of realizing superconductive filters capable of handling 30-50 watts with a third order intercept point of 100 dBm has been demonstrated in [5].

Cooling requirements

There are two ways to provide cooling in space: passive and active cooling [6]. Although passive cooling technology is well established and reliable, its application would necessitate a considerable change in the spacecraft structural design. Active cooling would allow more control over the process and is more compatible with present designs, but it would add demands to the satellite power system. Present mechanical coolers are not yet reliable enough to last 10 years , but progress is being made and there are realistic possibilities of active coolers with smaller mass and power consumption capable of meeting the reliability requirements over the mission life of the spacecraft.

PROCESS DEVELOPMENT

Microstrip devices consist of a dielectric substrate with a patterned HTS film on the top side and a complete HTS or metal coating on the substrate backside which serves as a ground plane. The substrate is then mounted in a conducting package. Microwave signals from coaxial cables are fed in through connectors. The first step in making a device is patterning the HTS thin film. An advantage of using HTS thin films to make microwave devices is that one can use lithographic techniques to fabricate designs with high precision. Since this technique is highly developed in the semiconducting device field, it is a good starting point for process development of HTS thin film devices. However, HTS materials are chemically and mechanically quite different than semiconductors and every step of the process must be checked and possibly modified. This can often be an iterative problem since the most sensitive tests may require a test device to be fabricated. Another complication is that the different HTS materials (e.g. YBCO and TBCCO) have different properties and even films of the same material which are grown by different techniques or the same technique but in different labs can have different properties.

Wet etching

We have tested the effects of standard positive photoresists and their developers on originally good quality HTS films. Microwave surface resistance measurements before and after simple treatments of HTS films with photoresist and developer do not show degradation.

The simplest method of etching a HTS thin film is by using a dilute acid wet etch. By experimenting with a number of acids it was found that for pulsed laser deposited YBCO films, grown at NRC, 1% phosphoric acid gives the least amount of undercut and the smoothest edges. Phosphoric acid does not etch TBCCO films and we use dilute hydrochloric acid for these. Wet etching can give large undercuts of a micrometer or more. This is greater than the precision desired for microstrip devices.

Tests show that wet etching damages the edges of the patterned YBCO. This is likely due to preferential etching of grain boundaries. In microwave applications, this is a major concern since the RF current tends to be concentrated at the edges of the devices. Degradation of the superconductor at the edges of patterns could have a large effect on the operation of a microwave devices.

Dry etching

In order to avoid the problems with wet etching, we have developed a dry etching process using argon ion milling to pattern the HTS films. The edges of the HTS film are shielded by a photoresist mask and we expect that the grain boundaries would not be attacked. There may still be some damage at the very edge of the pattern. We have found evidence for some oxygen loss in YBCO due to ion beam heating of the film in a vacuum. Samples are mounted on a water cooled copper holder and the ion milling rate is kept low to minimize this. The thallium based superconductor is not as susceptible to oxygen loss as is YBCO.

As a test for the amount of damage caused by ion beam milling, we thinned YBCO films on sapphire substrates. In one case, a 20 μm wide line was fabricated from an originally 200 nm thick film and was thinned down to a thickness of 40 nm by ion milling. We used a 500 eV beam with a current density of 0.2 mA/cm^2 and perpendicular incidence. At this thickness the YBCO was transparent in appearance. The room temperature resistivity of 215 $\mu\Omega \cdot$cm and the 100 K resistivity of 84 $\mu\Omega \cdot$cm are indications of good quality YBCO. A voltage vs current measurement (Fig. 3) shows a relatively sharp onset as the voltage rises from zero. This indicates a uniform film rather than one with areas of weak and strong superconductivity. A critical current density of 2.7 x 10^6 Acm^{-2} is very good, especially for YBCO on a sapphire substrate. The zero resistance critical temperature was 85 K as compared to a T_c of 88 K in unthinned parts of the same sample. This lower T_c may be due to some surface damage but it could also be due to the small thickness of the film. Another sample was thinned to a thickness of 80 nm with similar results but its T_c was 86.5 K. The above measurements were made after the samples were annealed in oxygen at 400°C. Before the anneal the resistance of the first sample was 2500 Ω and the anneal lowered it to 1800 Ω. So the sample did lose oxygen but the loss was reversible and there was not much damage to the crystal structure.

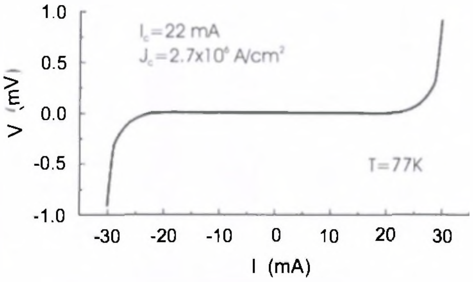

Fig. 3 **Voltage versus current for a 20 μm wide YBCO track, thinned to 40 nm by ion milling.**

At this point we have a pretty good process for patterning microwave devices from HTS films. The most sensitive tests must come from making actual microwave devices and testing them. We need to design devices, for example resonators, from which we can determine such properties as losses and power handling, of the HTS film. It is important to do this at microwave frequencies where the current distribution and the loss mechanisms are different than at low frequencies.

Contacts

Microstrip packaging requires that electrical contacts with resistance much less than one ohm be made to the HTS film. One must be able to make a mechanically strong wire bond to the contact. YBCO films can have an insulating layer form on their top surface during the originel film growth or during subsequent storage and processing. This leads to the state of the surface of YBCO films being quite varied.

Gold and silver are the metals which are most chemically compatible with the HTS oxides, since they don't easily react chemically with oxides. Simply evaporating Au or Ag onto untreated YBCO films produced films with poor to almost no adhesion. The films with enough adhesion to wire bond to had large resistances. Typically, a 400 μm x 400 μm contact would have a resistance in the range of 10 to 100 Ω. Chemically cleaning the surface of the film can result in contacts with a resistance less than 0.1 Ω, but it does not give consistent results.

The surface cleaning problem can be solved by ion milling at a 60° angle of incidence and then evaporating, *in situ*, a Au or Ag contact. This method gives reliably low resistance and good adhesion. The resistance of 400 μm x 400 μm contacts is always less than 0.1 Ω and are usually in the 0.01 Ω range. A typical voltage versus current (IV) measurement is shown in Figure 4.

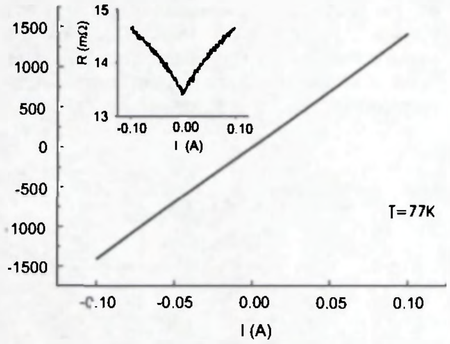

Fig. 4 Current versus voltage for a pair of contacts in series for Au on YBCO. The inset shows the first derivative.

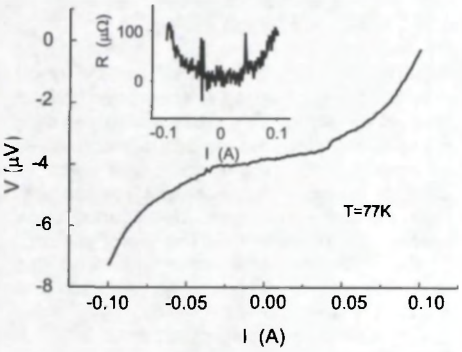

Fig. 5 Current versus voltage for the same pair of contacts as in Figure 4 after annealing. The inset again shows the first derivative.

IV measurements indicate that the contacts have a tunnelling nature. We believe this is due to a thin layer of oxygen poor YBCO immediately under the contact. The wire bond strength of contacts with 200 nm to 300 nm of Au were 5 to 7 g of force which is about at the lower limit of the strength needed for commercial applications. With a thicker metallization, 0.7 to 1 μm, the bond strengths are over 10 g, which is satisfactory for commercial use. When these contacts are annealed at 450 °C in oxygen the resistance is further lowered to values around 1×10^{-5} Ω. An IV of an annealed contact is shown in Figure 5 with an inset to indicate the reduced contact resistance.

The anneal re-oxidises the YBCO at the contact interface, which lowers the contact resistance, and there may be some diffusion of the metal into the YBCO which would increase the bond strength. An anneal at a higher temperature should further increase the bond strength and reduce the contact resistance [7].

We have found that making contact to TBCCO films was relatively easy. The testing was limited to films from a single commercial source. Applying a Ag contact by sputtering to a TBCCO film with no special cleaning yields contact resistances around 2×10^{-3} Ω with adequate adhesion for bonding. Using an ion beam clean followed by an evaporated Au contact gave even lower resistance values of 4×10^{-6} Ω as well as improved adhesion. The TBCCO films were not annealed and the low resistance indicates that there is little oxygen loss from the surface.

Filter performance

We have built HTS microstrip filters with good performance. Figure 6 illustrates the measured performance of a 3-pole planar microstrip filter with a 4 % bandwidth constructed on double-sided TBCCO wafer. In the figure, each horizontal bar is a half-wave resonator. The coupling between the resonators is determined by the offset of the middle resonator. The filter is coupled directly to 50 Ω microstrip transmission lines which are the vertical lines in the figure. This type of filter was described in reference [8]. The performance at 300 K of an identical filter built using Au films is also shown in this figure. The performance would not improve much if the Au filter was cooled to 77 K. It can be seen that the superconductive filter offers more than 3.5 dB improvement in the insertion loss performance. The HTS filter circuit is packaged in a carrier made out of aluminium-copper alloy of size 0.6"x.75"x 0.4" [9]. A filter built using conventional dielectric resonator technology, to achieve the same RF performance shown in Figure 6, would have a volume that is ten (10) times the volume of the HTS filter.

PASSIVATION

The HTS film must be protected from the environment during package assembly and for the rest of the device lifetime. HTS films are very sensitive to even very weak acids. Water condensed out of the air can be acidic enough to attack the film. One approach is to coat the device with a polymer such as polyimide. This material can be spun on and then cured by baking. This yields a rugged and inert coating.

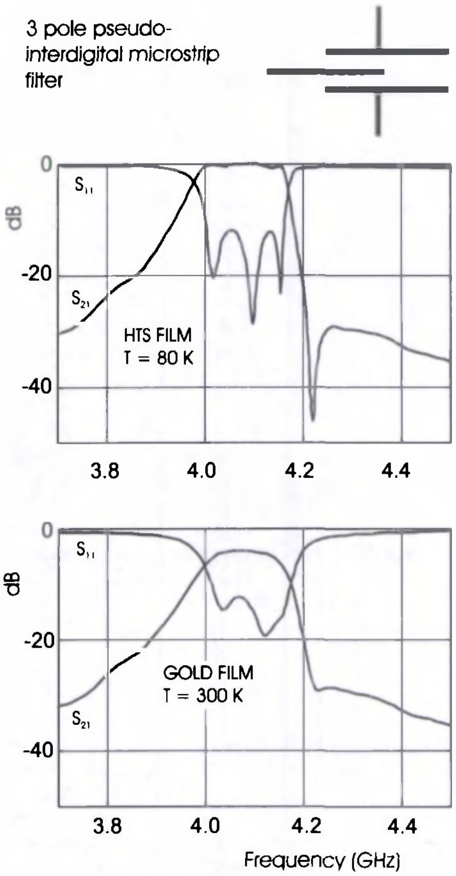

Fig. 6 The measured performance of a 3 pole microstrip filter showing the performance increase enabled by HTS films.

However, polyimide does absorb a significant amount of water and this may cause HTS film degradation in the long term. There is also a concern that organics may interact with the HTS film, so the organic protection film itself has the potential to be a problem. Inorganic protection coatings such as Al_2O_3 or SiO_2 are more compatible with the HTS oxide surface. They can be deposited by evaporation, but there can be a problem with pinholes. These oxides are good protection layers against some chemicals but not others. A scheme of passivation that we are in the process of testing uses a combination of the two. We start by coating the microwave device with an oxide, in our first tests we are using Al_2O_3, and spin coat this with a polymer. If the protection layers are applied before the device is packaged, then these layers must be patterned to have openings on the contact pads. We have developed methods to pattern both types of protection layer. Short term tests have produced good results and we have packaged a number of microwave resonators to use in long term tests.

CONCLUSIONS

The HTS technology offers the potential of large reduction in mass and volume of electronic equipment, leading to significant cost reduction for satellite systems. It could also provide performance discrimination not attainable with other technologies. However, a number of hurdles still remain before this technology is likely to be deployed for commercial satellite systems. These include the availability of light-weight reliable cryo-coolers and the qualification of the HTS materials for space environment.

The quality of HTS films and substrates and the quality of the processing is not high enough to reliably manufacture commercially useful microwave devices. Steady advances have been made in recent years in both these areas and the progress should continue. Careful measurements on properly designed devices are needed to determine the limitations in the present devices and whether these can be improved by process or material changes or are due to fundamental HTS properties.

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The following article was printed in The Ottawa Citizen on Sept. 19th. It was the product of a collaborative effort on the part of the Canadian Federation of Biological Societies (CFBS), the Canadian Association of Physicists (CAP) and the Canadian Society for Chemistry (CSC). This action arose out of efforts by the CAP to draw attention to the implications of the cuts within AECL, but clearly raises broader issues of concern to the wider scientific community. It is believed that the primary result of such an article will be to demonstrate to a lot of people that the science community is indeed acting collectively more and more. That's an important message to convey not only to the political world, but also to the public and to our own constituencies. Comments most welcome. If anyone would like a "real" copy of the article, please let the CAP Office know.

BACKGROUND

In an unprecedented open letter this week, Nobel laureates, laboratory directors and more than 700 scientists from across Canada and around the world urged the federal government to save a unique nuclear research facility at Chalk River from closing. In this article the presidents of three of Canada's largest scientific organizations detail an even greater threat to the country's competitiveness in science and technology.

By Vedene Smith (CSC), Beverly Robertson (CAP) and Judy Anderson (CFBS), Special to the Citizen

Even though overall support for science and technology in Canada is much less than in our major trading competitors, Canadian scientists have accepted that science must bear its share of cuts to reduce government deficits. The problem is that science and technology are taking a disproportionately large share of the cuts, in both government laboratories and universities. Federal government departments which include in their mandate some aspect of science and technology have dropped or curtailed their science and technology activities, especially the long-term work. If one laboratory closes down, perhaps we can get away with worrying about it later. However, when the phenomenon affects research programs in Industry Canada, Health Canada, Agriculture Canada, Environment Canada, Fisheries and Oceans and Natural Resources Canada, all acting independently but in isolation, the Canadian economy cannot escape the consequences.

Reacting to challenge

Similarly, long-range research in industry, and all research in Canadian universities, is being severely cut. Industrial research is reacting to the challenge of global competition by further concentrating on the immediately applicable. Provincial governments are reacting to the cuts in federal transfer payments for social programs by encouraging their universities to minimize the impact on their educational function and to let the research function bear the brunt of the squeeze. The result is less time for research and much reduced support for infrastructure such as computing hardware and software, libraries, machine shops and technical support. This reduction places ever greater demands on the diminishing federal research grants for operating costs. In order to preserve the feedstock of ideas and maintain some reasonable balance between short-term and long-term research, the Japanese government concluded it should double government support for long-term research. The recently released federal study on management structures for internal government research (Science and Technology for the New Century) has called for exactly the reverse for internal federal government research in Canada. Natural Resources Canada has announced plans to drop $20 million of long-term research, including the facility used by Canada's most recent Nobel laureate, Bertram Brockhouse. The expiry of the $35 million Green Plan will shut down much research, such as most of the activity at the Experimental Lakes Area near Kenora and the Freshwater Institute in Winnipeg. These national research facilities and the research carried on in universities are not only sources of new ideas and new jobs for Canadians, they also allow Canada to participate in the international research network, and thereby provide Canada fast access to research conducted in the rest of the world. Such access is essential; who could have predicted that software created by a group of physicists at a major European research facility (CERN), to better share their research results, would lead to the new communication tool called the World Wide Web? This component of the information highway has the potential to change the conduct of the world's business in unknown ways. Can Canada afford to learn about such developments after the rest of the industrialized world?

Youth employment

The federal government professes to consider youth employment a priority. If Canada moves from being a country in which roughly half as much research is done per capita as by its G-7 competitors, to one in which perhaps a quarter as much research is done, should we really expect the future job market faced by Canadian youth to be better than the present? The low priority given to overall science and technology policy in Canada leads to decisions that reduce research support being taken in isolation, without regard to their destructive and cumulative impact. Leadership and coordination are essential to make science and technology a positive force in the new economy. The Canadian science community is ready to provide assistance toward this end.

BOX

Key Proposals

Here are essential actions proposed by three of the largest groupings of Canadian scientists - chemists, physicists, biologists and biomedical researchers:

1. Include a significant component for research infrastructure - for equipment, repairs; operators and other research support people - in the infrastructure II program.
2. Assess government science cuts and program changes to identify gaps, strengths and new directions.
3. Assemble scientists, economists and government decision-makers to define the needs of, and the means to, sustain Canada's science and technology enterprise.
4. Begin an annual open and rigorous assessment of government support of science and technology and of the directions Canadian science must pursue.