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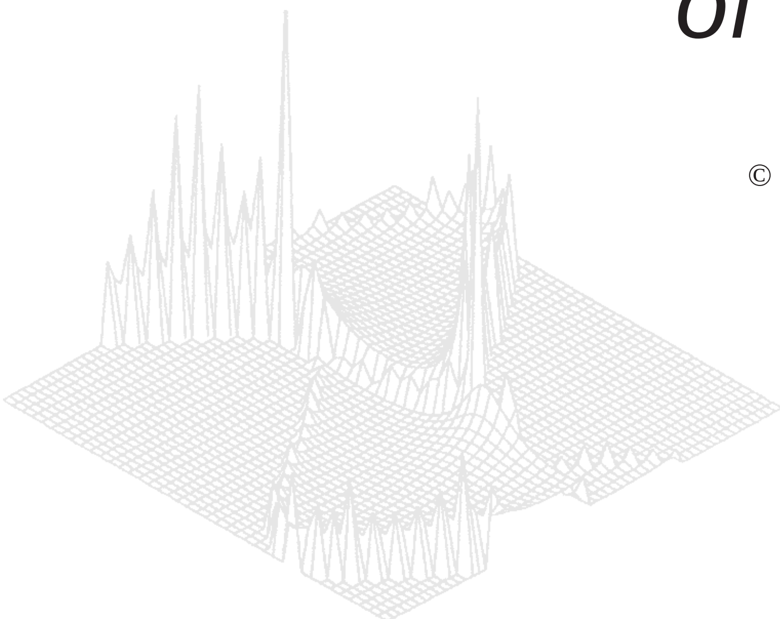

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Application of High Temperature Superconductors in Passive Microwave Devices*

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Abstract

The front end of a microwave communications system is assembled from circuit elements comprising antennae, local oscillator, mixer and filters. Interconnection is by transmission line, into which delay may be incorporated. All of these components can, with advantage, be implemented in superconducting material. Superconductors, when operating below their cross-over frequency, have values of surface resistance lower than those for normal metals such as copper and silver. This results in lower insertion loss for microwave components, allowing the design of smaller, more compact, yet at the same time more complicated, devices. The non-dispersive nature of superconductors can also be an advantage in enabling very high bandwidth signal processing. High temperature superconductors (HTS) allow operating temperatures in the liquid nitrogen range, not too far below the ambient temperature in many communications satellites. The Oxford microwave programme has concentrated on the implementation of all of the above devices in thin-film HTS, mainly Tl-2212, on a variety of substrates. The film fabrication, and performance of delay lines, antenna-mixers, resonators, filters and a voltage-controlled oscillator, are described.

1. Introduction

The highest quality samples of high temperature superconductors are in the form of small area thin films, and it is for this reason that the first commercial applications of HTS will be in passive microwave systems. Microwave communications systems offer many opportunities for the application of superconductivity. For example, a typical microwave receiver front end, shown schematically in Fig. 1, consists of an antenna, mixer, local oscillator, phase shifter and filters, interconnected by transmission line. All of these individual components are capable of implementation in superconducting materials. However, there must be some real advantage in superconductor over normal conductor in order to justify the replacement of the latter by the former. Unlike operation under DC conditions, at high frequencies superconductors are not lossless; but their surface resistance R_s may be much lower that of copper or silver, the normal conducting metals usually employed in microwave components. This results in lower insertion losses for superconducting components, allowing for the design of smaller and more compact circuits and systems with reduced operating power requirements. It is even

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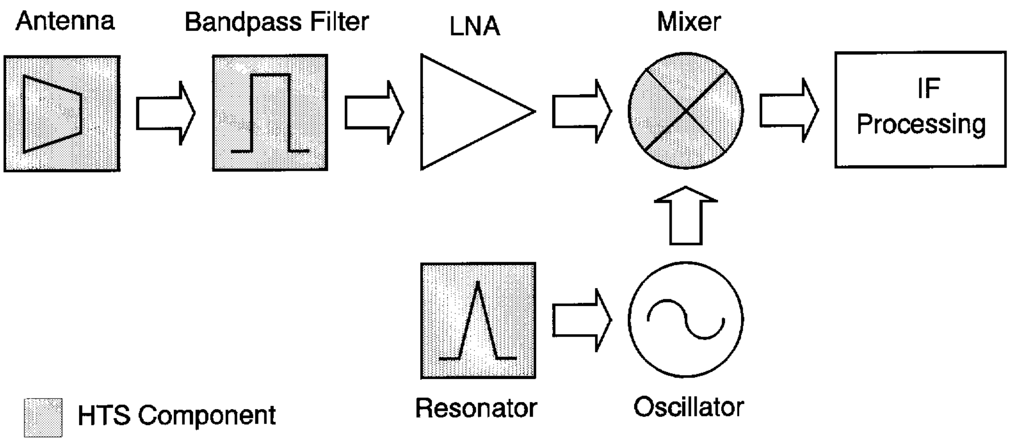

Fig. 1. Schematic of a microwave receiver front end, indicating the components that can be implemented in HTS.

possible to contemplate very complicated component and system architectures which would be far too lossy to be implemented in normal conductors (Jenkins *et al.* 1993*a*, 1994). Superconductors can also transmit high frequency signals without dispersion.

However, a price has to be paid for these advantages. No superconductor has yet been discovered that is superconducting above 150 K, let alone at room temperature, and all superconductors must be cooled to well below their critical temperatures for useful operation in practical devices. The fact that the ambient temperature in a satellite is about 100 K, coupled with the more compact circuitry and reduced power requirement, makes HTS microwave systems particularly appropriate for satellite communications (Jackson and Bhasin 1994), avionics and radar (Ryan 1994). HTS superconducting devices have been successfully integrated with hybrid microwave circuits (Shen *et al.* 1993).

2. Theory

Superconductors are lossy at high frequencies because, although electron scattering is suppressed in the superconducting state, the superelectrons still have momentum and, except at the lowest temperatures, normal electrons are present which also contribute to the high frequency conductivity. The superconducting state, at a frequency ω, can be represented by a complex *effective conductivity*:

$$\sigma_{\mathrm{eff}} = \frac{1}{\omega\mu_0\lambda^2}\left[\omega\tau\left(\frac{n_{\mathrm{N}}}{n_{\mathrm{S}}}\right) - j\right], \tag{1}$$

where λ is the penetration depth and τ is the scattering time of the normal electrons. Here n_{S} and n_{N} are the number of electrons per unit volume in the superconducting and normal states respectively; $n_{\mathrm{S}}+n_{\mathrm{N}} = n$, the total number of electrons.

In the normal state the surface resistance and the surface reactance are equal and proportional to the square root of the frequency:

$$R_{\mathrm{S}}(N) = X_{\mathrm{S}}(N) = \left(\frac{\omega\mu}{2\sigma}\right)^{1/2}, \tag{2}$$

while in the superconducting state, provided $(\omega\tau)^2$ is very much less than 1, i.e. at frequencies less than 10^{12} Hz, they are given by

$$R_{\mathrm{S}}(S) = \frac{\omega^2\mu^2\lambda^3}{2}\,\sigma_n(n_{\mathrm{N}}/n)\,, \qquad X_{\mathrm{S}}(S) = \omega\mu_0\,\lambda\,. \tag{3}$$

Note that the different frequency dependence in the two states means that for any superconductor there is a frequency, the *cross-over frequency*, below which the superconductor always has a surface resistance lower than that of the normal state (Piel *et al.* 1992). The cross-over frequency is a function of the superconductor and its degree of structural perfection; for HTS thin films at 77 K it can lie in the range 10–100 GHz. The temperature dependence of R_{S} is contained in the temperature dependence of both λ and n_{S}. The dependence on (frequency)^2 is used to scale results taken at different frequencies, but such comparison should also be taken at the same reduced temperature with respect to the critical temperature of the superconductor.

The dispersion relation for a superconductor is

$$k^2 = \mu_0\,\epsilon\omega^2 + j\omega\mu_0\,\sigma_n(n_{\mathrm{N}}/n) \tag{4}$$

from which it can be seen that, at temperatures sufficiently low that n_{N} is approximately zero, i.e. below about one half T_{c}, the second term can be ignored, the wave number k is directly proportional to ω and the behaviour is non-dispersive, with signals at different frequencies being propagated at the same velocity. This is, of course, a great advantage when information over a range of frequencies is being routed from one device to another within the same circuit.

3. Superconducting Thin Films

HTS thin film fabrication and implementation of microwave components at Oxford has concentrated on the thallium-based mixed oxide ceramic superconductors. With critical temperatures in the range of 100–125 K, they offer the possibility of superior performance to their Bi-based counterparts and to the 123 (YBCO-type) phases, particularly at liquid nitrogen temperature, 77 K, at the temperature readily attained by single-stage cryocoolers, ~80 K, and at satellite ambients, ~100 K. In comparison with YBCO 123 films, the thallium films are still in the relatively early stages of development. Nevertheless, performances comparable with those of the best YBCO films have been achieved. Tl-2212, Tl-2223 and Tl-1223 have been successfully deposited on a variety of substrates, $LaAlO_3$, MgO and ceria-buffered sapphire. The objective has been to produce device quality films for the implementation of passive microwave devices.

Film characterisation includes structural information derived from XRD, SEM and TEM, and the superconducting properties T_c, J_c (77 K) and surface resistance R_s (T). The latter is measured using end wall replacement or partial end wall replacement of a nominally 40 GHz (actually 39·3 GHz) cavity (Jenkins *et al.* 1996). The design and performance of devices based on these films have already been described (Dew-Hughes and Jenkins 1995; Jenkins *et al.* 1995*a*, 1995*b*, 1995*c*).

(3a) Substrates

Optimum superconducting properties require that the films be epitaxial 'single crystal' with texture such that the *c*-axis is normal to the plane of the film. The substrate acts as a template for the developing film, and its choice is partly dictated by a similarity of lattice parameter between superconductor and substrate. The substrate is also an important part of the microwave circuit and its dielectric properties must be compatible with the proposed application. The relative dielectric constant e_r is an important circuit parameter; it should be $\sim$10 and independent of temperature in the region of the operating temperature of the device. The loss tangent of the dielectric may dominate the total insertion loss of the circuit, and tan δ must be $<10^{-4}$.

The best substrate for epitaxial growth of many of the HTS compounds is $SrTiO_3$, but this is totally unsuitable as a dielectric in a microwave circuit as its behaviour is similar to a ferroelectric with a large and variable dielectric constant and very high loss tangent. The outstanding substrate material from the dielectric point of view is sapphire, Al_2O_3, with ϵ_r in the range 9·4–11·6 and tan δ one of the lowest known at $<10^{-6}$ (Hollmann *et al.* 1994). It has good mechanical strength and is readily available in the form of high quality, large area, wafers at low cost. Unfortunately, sapphire reacts with the superconducting compounds and their superconducting properties are degraded by the incorporation of aluminium. The use of sapphire as a substrate requires the interposition of a buffer layer.

Compromise candidates are $LaAlO_3$ and MgO. Both can have tan $\delta<10^{-5}$, ϵ_r for MgO is 9·6–10, whereas it is as high as 20–27 for $LaAlO_3$ (Hollmann *et al.* 1994). This high value can be of advantage at the lower frequencies, below about 10 GHz, as the size of circuit components are reduced. However, standard commercial CAD packages cannot treat components with relative dielectric constants above $\sim$15. A further disadvantage of $LaAlO_3$ is that it transforms from cubic to rhombohedral at about 500°C; the twinning accompanying this transformation causes surface roughness and a 2% anisotropy in the relative dielectric constant. Single crystals are expensive to grow, particularly in diameters >50 mm. High quality, epitaxial, films of both YBCO and Tl-based compounds have been grown on $LaAlO_3$. The lattice match with MgO is less perfect, and the material is hygroscopic which may affect the properties of any film grown upon it.

The Tl-based films described in this paper have been deposited upon $LaAlO_3$, MgO and ceria-buffered R-plane sapphire.

(3b) $Tl_2Ba_2CaCu_2O_8$ *(Tl-2212)*

There is an excellent lattice match between Tl-2212 and $LaAlO_3$, with $a_{2212} = 0{\cdot}386$ nm (Subramaniam *et al.* 1988) and $a_{\mathrm{LaAlO3}} = 0{\cdot}389$ nm (Werder and Liou 1991), and epitaxial films with critical temperatures of up to 107 K (Holstein *et al.* 1992*a*) and critical current densities of up to 7×10^6 A cm^{-2} (Yan *et al.* 1994) have been reported for films of Tl-2212 on $LaAlO_3$.

In the Department of Materials at Oxford Tl-2212 films are fabricated on $LaAlO_3$ substrates up to 50 mm dia by a two-stage process. Amorphous BaCaCuO precursor films are deposited onto the substrate by RF magnetron sputtering in $1\cdot8\times10^{-2}$ mbar argon from a pressed powder target of composition $Ba_2Ca_{1\cdot2}Cu_{1\cdot6}$. The superconducting Tl-2212 phase is subsequently formed during a 30–40 minute *ex-situ* thalliation anneal at 845–855°C in the presence of Tl_2O vapour provided by powder of the desired final composition. This process produces films which are smooth, well-connected, single-phase Tl-2212 highly aligned with the *c*-axis perpendicular to the plane of the substrate.

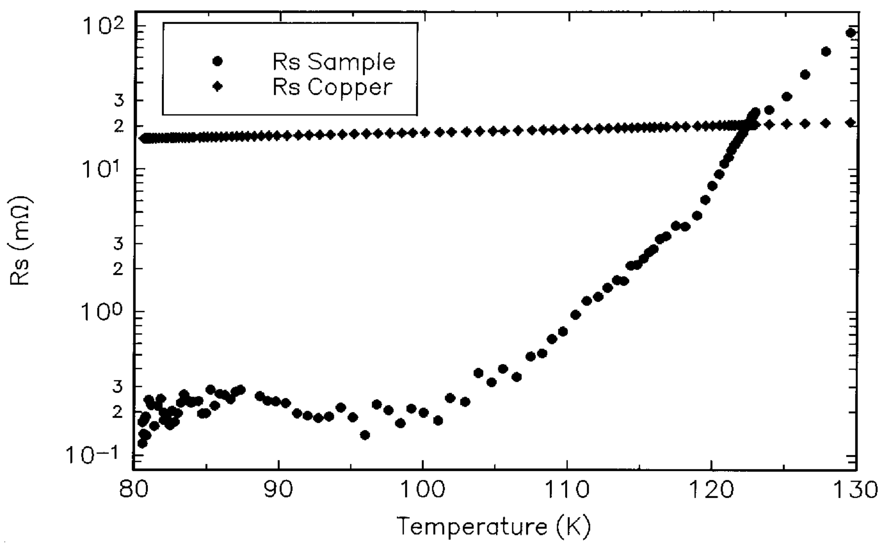

Fig. 2. Surface resistance versus temperature for a Tl-2212 film on $LaAlO_3$, measured at 40 GHz and adjusted to 10 GHz.

Microwave measurements were carried out at a frequency of $39\cdot3$ GHz over the temperature range 130–80 K. Assuming a (frequency)^2 relation to hold, the surface resistance results were scaled to 10 GHz as shown in Fig. 2, where it can be seen that at 80 K R_s for the superconductor is two orders of magnitude lower than that for pure copper. The lowest R_s value obtained, $2\cdot73$ mΩ at 80 K and $39\cdot3$ GHz, equivalent to 177 $\mu\Omega$ at 10 GHz, was achieved on a 20 mm square film and compares well with the best reported value for Tl-2212 of 130 $\mu\Omega$ at 77 K and 10 GHz (Holstein *et al.* 1992*a*). Values of the order of 200 $\mu\Omega$ (10 GHz; 80 K) are now being routinely obtained for these films.

The advantages of sapphire as a substrate material have been enumerated above. Two planes in the sapphire lattice are suitable for HTS deposition; the M-plane (1010) and the R-plane (1102). The latter gives the closer lattice match but the dielectric constant is anisotropic in this plane. HTS films deposited directly onto sapphire are of poor quality; the lattice mismatch is large, with $a_{\text{R-plane}} = 0 \cdot 348$ nm (Wu *et al*. 1992), and an interfacial layer of $BaAl_2O_4$ forms as aluminium atoms diffuse into the HTS film. These problems can be overcome by the deposition of an intermediate buffer layer. Provided the thickness of the buffer layer is small in comparison with those of film and substrate, the dielectric properties of the buffer layer material are of no consequence. Ceria, CeO_2, has been used successfully as a buffer between sapphire and YBCO (Wu *et al*. 1992), due to the excellent lattice match, the ease of control over ceria deposition and the stability of ceria in contact with YBCO at the deposition temperatures of the order of 750°C (Wang and Wordenweber 1993). At temperatures above about 790°C there is a reaction to form $BaCeO_3$, degrading the properties of the superconducting film. This has serious implications for the use of ceria-buffered sapphire as a substrate for Tl-2212, as the process employs a thalliation anneal at about 850°C. Initial attempts to deposit Tl-2212 on ceria-buffered sapphire using the standard thalliation process resulted in films with critical temperatures up to 94 K and critical current densities of 8×10^4 A cm^{-2} (Bramley *et al*. 1995). These results compare well with the only other reported deposition of Tl-2212 films on ceria buffer layers (Holstein *et al*. 1992*b*), but are markedly inferior to films deposited on $LaAlO_3$, as described above. Transmission electron microscopy of a transverse section of this film revealed the presence of a reaction layer of $BaCeO_3$ (Grovenor *et al*. 1994).

To prevent the formation of this reaction layer a low temperature thalliation process has been developed (O'Connor *et al*. 1995). The lower temperature requires a reduction in the partial pressure of oxygen accompanied by an increase in the annealing time to accomplish complete thalliation of the superconducting layer. A ceria buffer layer is deposited by RF sputtering from a pressed powder target, using a 10% O_2/Ar mixture at $1 \cdot 5\times10^{-2}$ mbar onto an R-plane sapphire substrate held at 775°C. BaCaCuO precursor films were subsequently deposited on top of the buffer layer, as described above. Thalliation is then carried out in an atmosphere, initially of pure argon, at 720–30°C for 90–120 minutes. Transverse TEM cross sections now reveal the absence of a reaction layer. HREM and electron diffraction results respectively confirm the absence of any reaction product and the presence of strong alignment of the HTS film on the ceria buffer layer (O'Connor *et al*. 1996). Films produced in this way have critical temperatures up to $101 \cdot 6$ K and critical current densities up to $1 \cdot 25\times10^5$ A cm^{-2}. Microwave measurements have been made on films 10 mm square. The lowest R_S at $39 \cdot 3$ GHz and 80 K to date is $46 \cdot 7$ $\mu\Omega$ which scales to $3 \cdot 02$ $\mu\Omega$ at 10 GHz. Work is continuing to bring these values closer to those obtained in films on $LaAlO_3$ substrates.

(3c) $Tl_2Ba_2Ca_2Cu_3O_{10}$ *(Tl-2223)*

Tl-2223 films with *c*-axis texture have been deposited on MgO despite the $9 \cdot 4$% lattice mismatch; $a_{2223} = 0 \cdot 385$ nm (Toradi *et al*. 1988) and $a_{\text{MgO}} = 0 \cdot 421$ nm (Hollmann *et al*. 1994). Such films can have critical temperatures as high as 122 K and critical current densities at 77 K of $1 \cdot 5\times10^5$ A cm^{-2} (Nabatame *et al*. 1990). In the Department of Materials, Tl-2223 has been grown on (001) MgO substrates up to 40 mm in diameter by DC magnetron sputtering from a target of approximate composition $Tl_2Ba_2Ca_2Cu_3$ in an atmosphere of 10^{-1}

mbar argon, followed by thalliation at 855–60°C. The quality of the Tl-2223 films prepared on MgO is very sensitive to the thalliation conditions, but despite this a reliable processing route has been established, and deposition on both sides of the substrate has been achieved. The films consist predominantly of single phase, *c*-axis-texture Tl-2223. Critical temperatures are 117 K and critical current densities at 77 K are $\sim 10^4$ A cm^{-2}. Excellent consistency of film quality has been achieved as evidenced by the R_S versus temperature plots for both sides of a film shown in Fig. 3. Measured values on either side of the film, at 39·3 GHz and 80 K are 20·70 and 23·94 $\mu\Omega$, which scale to 1·34 and 1·55 $\mu\Omega$ at 10 GHz.

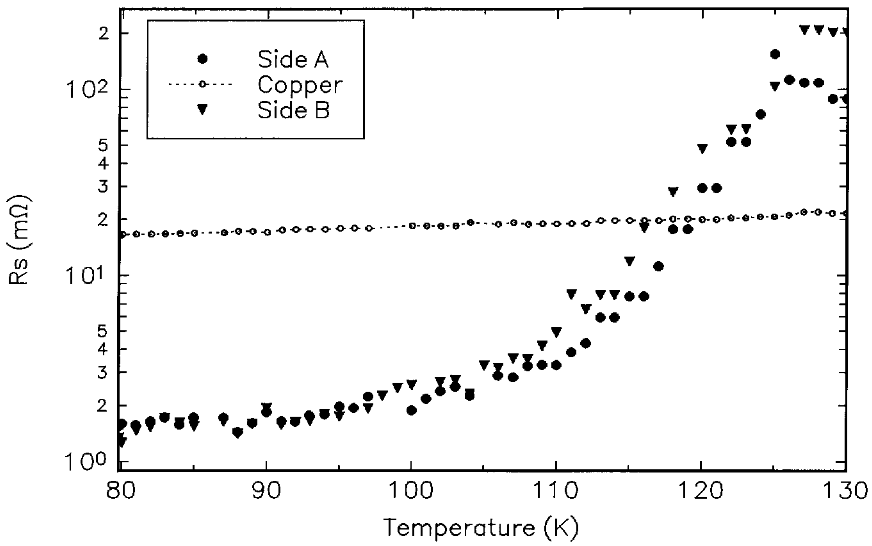

Fig. 3. Surface resistance versus temperature of both sides of a double-sided Tl-2223 film on MgO, measured at 40 GHz and adjusted to 10 GHz.

(3d) $TlBa_2Ca_2Cu_3O_9$ (Tl-1223)

There is interest in the single thallium-layered phases as their ability to carry large current densities is less sensitive to the application of magnetic fields than that of the double-layered thallium phases. This is attributed to the stronger coupling of the superconducting wave functions between groups of Cu–O planes in the single-layered structures. These compounds have high critical temperatures, up to 121 K for the Tl-1223 phase (Morosin *et al.* 1991). The formation of high quality Tl-1223 is not easy, but the phase can be stabilised by partial substitution of lead for thallium (Glassey 1995).

$Tl_{1-x}Pb_xBa_2Ca_2Cu_3O_y$ films have been grown from TBCCO precursors deposited by DC magnetron sputtering onto 10×10 mm^2 $LaAlO_3$ substrates. The method is identical to that described above for the Tl-2223 films, with the exception that the lead dopant is incorporated into the films during the thalliation stage, when a small quantity of PbO_2 powder is mixed with the Tl-2212 powder used as a source of Tl_2O vapour. Thalliation is carried out for 75 minutes at 860°C. The films are predominantly c-axis aligned Tl-1223. The films consist of well connected platelets of Tl-1223, with some small surface particles of CuO. The films have critical temperatures up to 103 K, and values of surface resistance at $39 \cdot 3$ GHz and 79 K of $39 \cdot 50\,\mu\Omega$, scaling to $2 \cdot 56\,\mu\Omega$ at 10 GHz. The surface resistance is probably degraded somewhat by the presence of the CuO particles.

4. Devices

Many microwave devices may be implemented from thin films of high temperature superconductors (Lyons and Withers 1990; Withers 1993). The following are examples of devices fabricated as a part of the applied superconductivity and communications programmes within the Engineering Science Department at Oxford University. Typical microwave components that have been developed at Oxford include delay lines, antennae and mixers, microstrip and cavity resonators, oscillators and filters. The Tl-2212 superconductor, deposited on MgO or $LaAlO_3$ substrates, has been used almost exclusively for these devices. The value of T_c is typically 105 K so that operation at 77 K represents a reduced temperature of $0 \cdot 7$ at which the relationships given above in the theory section are expected to hold with reasonable accuracy.

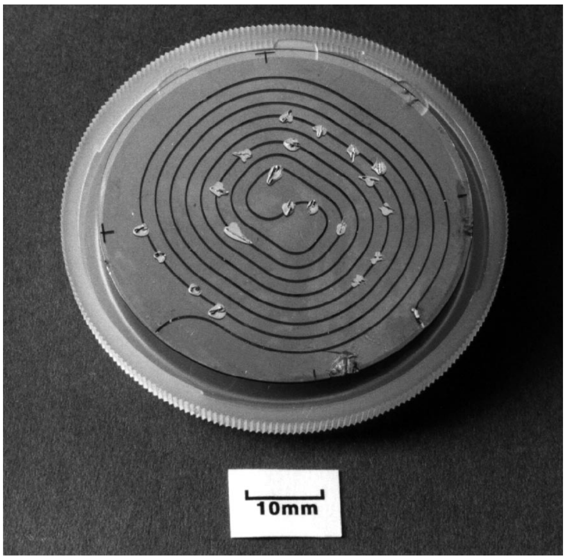

Fig. 4. Delay line patterned from Tl-2212 film on $LaAlO_3$. (The silver 'blobs' are contacts for measuring the critical current of different sections of the line, after measurements of insertion loss and delay had been made.)

(4a) Delay Lines

The amplitude of a wave propagating down a transmission line of thickness d, very much less than its width, decays exponentially with distance z multiplied by the propagation constant α which is directly proportional to the surface resistivity:

$$V(z) = V_0 \exp(-\alpha z)\,, \qquad \text{where} \quad \alpha = \left(\frac{\epsilon}{\mu_0}\right)^{\frac{1}{2}} \frac{R_S}{d}\,. \tag{5}$$

The advantage of superconducting delay lines, with their much lower values of R_S is obvious. A microstrip delay line has been fabricated from a Tl-2212 film deposited on a 50 mm diameter $LaAlO_3$ wafer (Dew-Hughes and Jenkins 1995). The structure, as shown in Fig. 4, was 640 mm in length, with a track width of 210 μm and spacing of 1·5 mm. The device demonstrated a mean insertion loss (at 77 K) of 3 dB over the measured 6 GHz bandwidth and a delay of 9 ns across the band. This is compared with the room temperature measurement in Fig. 5. The combination of these results yields a loss per delay figure of merit of 0·3 dB ns^{-1}, which compares favourably with the work of others (DuPont 1993).

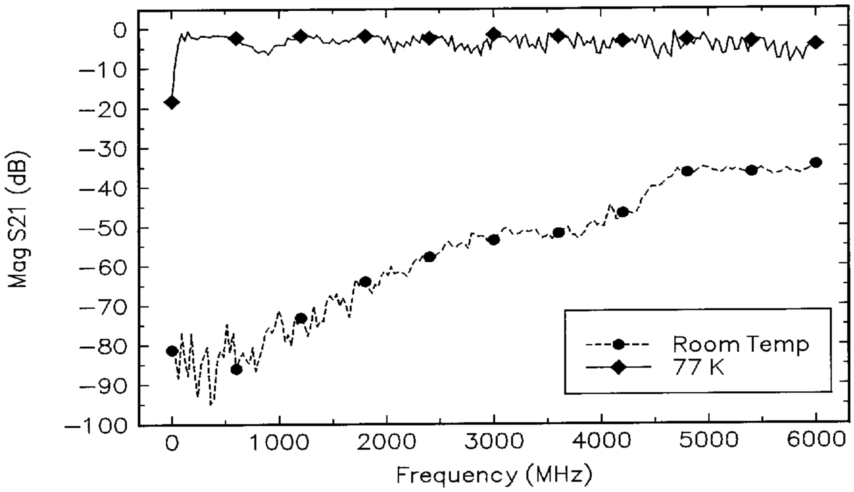

Fig. 5. Insertion loss versus frequency, at room temperature and at 77 K, for the delay line of Fig. 4.

Chirp filters (Withers and Ralston 1989) have been fabricated from large area films, and tapped delay lines have been proposed for spread spectrum correlators (Jenkins *et al.* 1993*a*, 1993*b*). The long delays that are required to make such devices are only feasible using HTS technology, since the attenuation in conventional conductors would be too great.

(4b) Integrated Mixer and Antenna

Another essential component in any microwave system is a mixer. It is possible to exploit the nonlinearities inherent in some HTS structures (grain boundaries, weak links, microbridges, etc.) to perform heterodyne mixing of microwave signals to down convert an RF signal under the action of an applied local oscillator (LO) to an intermediate frequency or IF. Also the single-layer planar nature of the active element makes it possible to integrate planar antenna elements with each mixer element, allowing the implementation of imaging and phased arrays (Chew and Fetterman 1989; Fukumoto *et al.* 1993).

Mixing elements, integrated with various antenna structures, such as those shown in Fig. 6, have been fabricated from Bi-2223 thin films on MgO substrates. Mixing was observed under the application of a 26 GHz RF signal and a sub-harmonic 12 GHz LO. A typical output power spectrum, in this case from a twin bow-tie dipole, is shown in Fig. 7 where a signal-to-noise of 60 dB and a

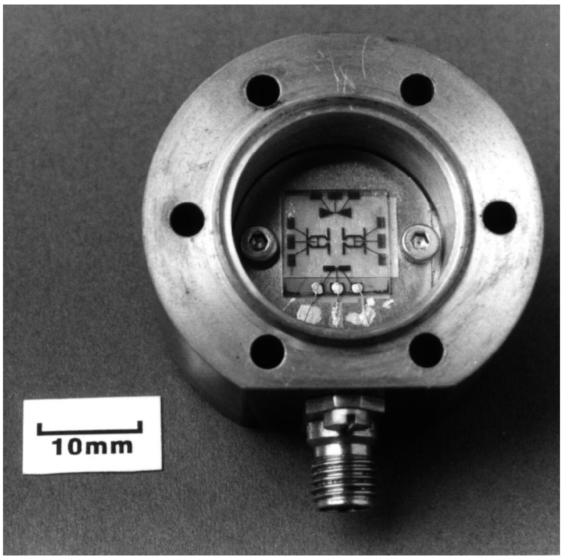

Fig. 6. A set of four antenna-mixers on a single substrate.

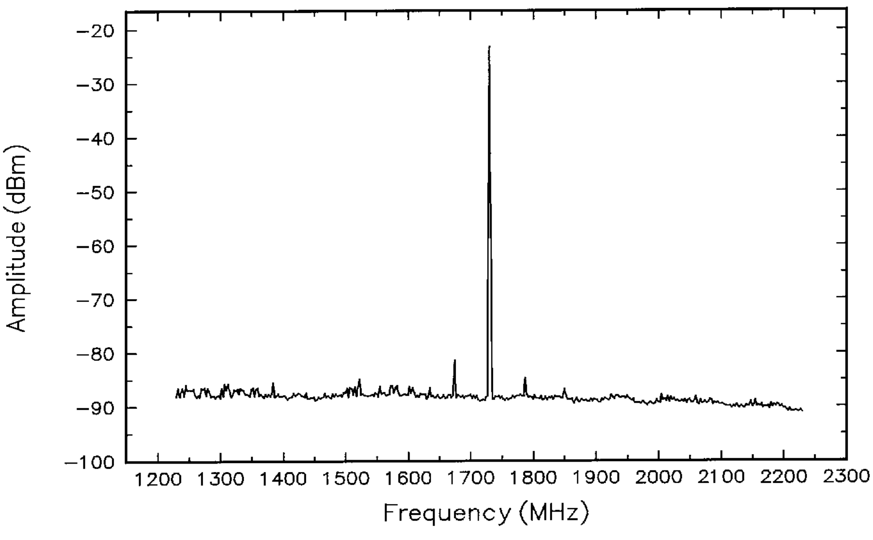

Fig. 7. Frequency response of an antenna-mixer, patterned from a Bi-2223 film on MgO, irradiated with 37 GHz from a Gunn diode oscillator mixed with the fourth harmonic from a 9 GHz local oscillator.

conversion gain of −38 dB was recorded. Mixing was also observed with other multiples of the sub-harmonic (Jenkins *et al.* 1995*a*).

(4c) Resonators

The quality factor Q of a resonator, which defines the width of the resonance, is inversely proportional to the surface resistance of the material from which the resonator is made. Superconducting resonators can be configured as strip-lines or as cavities, and their low values of surface resistance can lead to Q-values of several thousand, compared with a few hundred in cooled copper or silver. Various forms of microstrip, end-coupled resonators have been investigated at Oxford. These have included both meander line resonators at 3 GHz on MgO (Morley *et al.* 1993) and lower frequency (1·4 GHz) resonators on $LaAlO_3$ wafers that are primarily designed as test devices as well as higher-frequency, linear resonators, designed for use as stabilising elements in a microwave oscillator (Jenkins *et al.* 1995*b*; Jones 1995).

Typical Q-values for 3 GHz resonators at 77 K are in excess of 2000, compared to 340 for a silver implementation of the same device. It has also been demonstrated experimentally that the resonator centre frequency is affected by an applied magnetic field (Jenkins *et al.* 1993*c*). This has applications in voltage controlled oscillators (VCO), as described in Section 4*e* below.

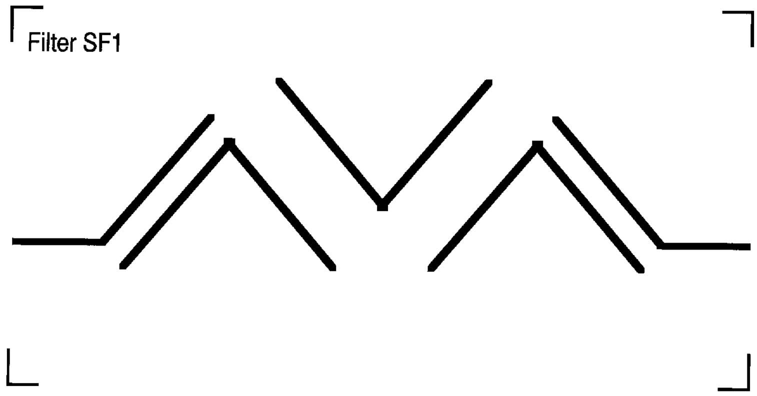

Fig. 8. Mask for a 3-pole, 6 GHz, 1% bandwidth, planar filter.

(4d) Filters

The above devices, which are the individual components of microwave circuits, have all been shown to have useful performance when implemented in superconductors. The next stage, the fabrication of a complete microwave communications system front-end, as indicated in Fig. 1, on a single substrate, requires the additional development of filters. Filters are essentially a set of resonators coupled in such a way as to allow the transmission of signals within a well-defined range of frequencies. The particular advantage of superconducting filters is the significant reduction in size; normal metal filters are large and heavy, cavity-like structures whereas in superconductor filters can be implemented as microstrip. An edge-coupled microstrip filter, the mask for which is shown in Fig. 8, has been designed to operate at a centre frequency of 6·3 GHz with a bandwidth of 1%. This device was patterned onto a double-sided Tl-2223/MgO film, fabricated as described in Section 3*c*, using standard photolithographic techniques and a wet etch of citric acid (Jenkins *et al.* 1995*c*). The frequency response, over a $2 \cdot 5$ GHz span, is shown in Fig. 9. The inset shows the detail around the pass band. The minimum pass band insertion loss, as measured to be $1 \cdot 2$ dB, is considerably less than 10 dB measured for a similar filter implemented in copper. The measured pass band matches that of the specification, 1%, but there is some detuning of the filter characteristic, due to incomplete coverage of the ground plane.

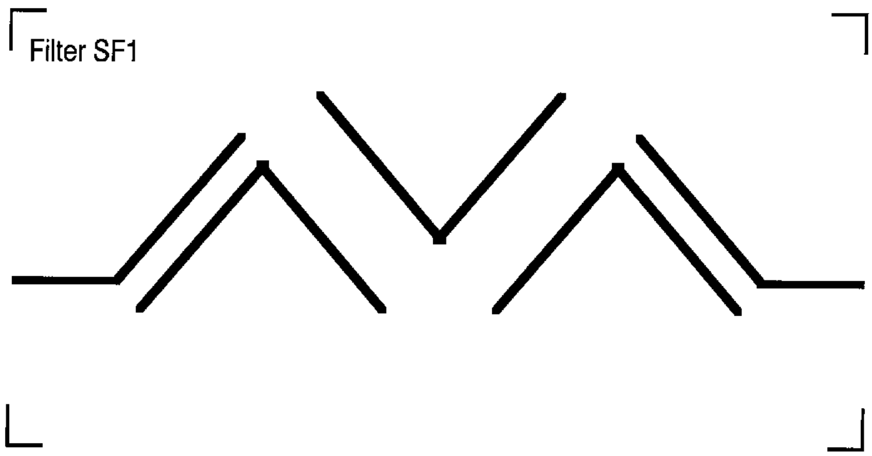

Fig. 9. Frequency response of a filter patterned from the mask shown in Fig. 8, on one side of the double-sided Tl-2223 film of Fig. 3. The inset shows an expanded scale over the range $6 \cdot 25$–$6 \cdot 45$ GHz.

Similar planar filters have been demonstrated by a number of other groups (Mattheai and Hey-Shipton 1993; MacDonald 1994), with performances comparable to normal metal cavity filters but at a fraction of the mass/volume. Dimensional accuracy is an important issue for this type of filter, when compared to conventional cavity filters as small changes in resonator length can significantly offset the centre frequency of the filter. An added bonus of using HTS materials is that filters can be designed using lumped elements incorporating inductors (Lancaster *et al.* 1993) and capacitors (Zhang *et al.* 1995).

(4e) Oscillators

Oscillators are key components of microwave sub-systems, and the basis of all oscillators is some type of resonator, which defines the frequency of operation and stability of the oscillator. Due to the lower surface resistance, resonators of higher *Q*-factor can be made from HTS than from copper, and the use of such HTS resonators can improve the performance of an oscillator (Jenkins *et al.* 1993*c*).

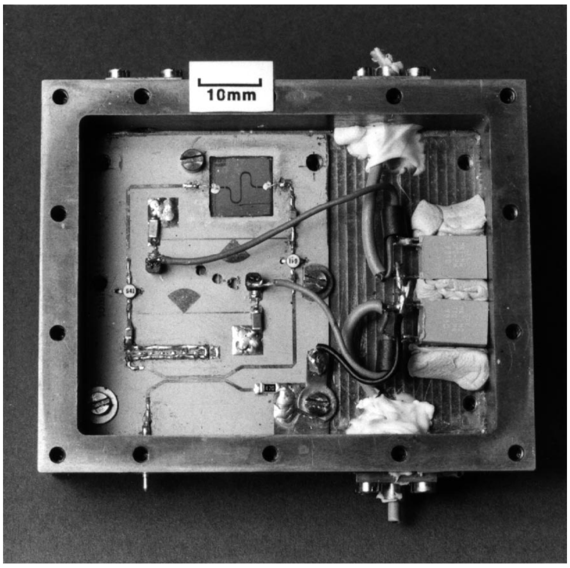

Fig. 10. The 3 GHz oscillator in its enclosure. The meander-line resonator can be clearly seen.

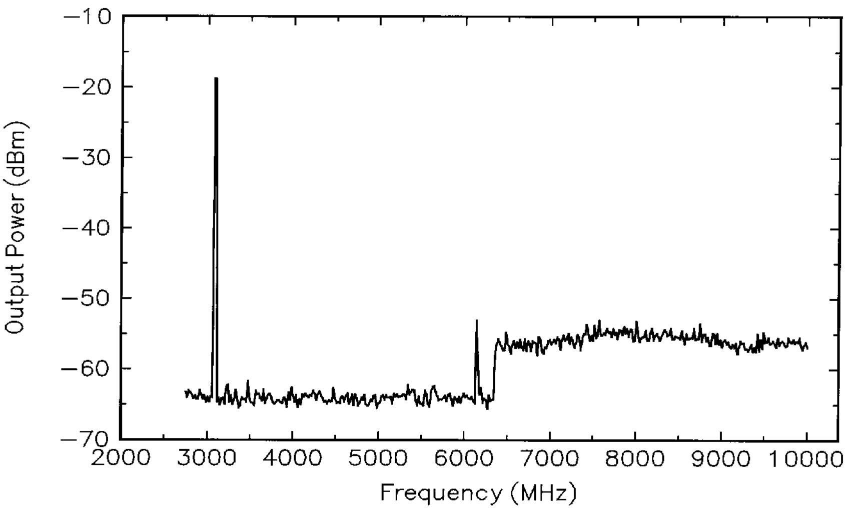

Fig. 11. Output of the 3 GHz HTS resonator-stabilised oscillator.

A microstrip HTS resonator stabilised oscillator has been developed based on a feedback structure, incorporating two GaAs MMIC amplifiers, integrated onto a common substrate and operated at 77 K with a centre frequency of $3 \cdot 1$ GHz (Jones 1995). Fig. 10 is a photograph of the oscillator, showing the positions of the active devices and the HTS resonator, which was fabricated from a Tl-2212 film on a $10 \times 10\ \mathrm{mm}^2$ $LaAlO_3$ substrate, deposited as described in Section 3*b*. Fig. 11 is the output of the oscillator (at 77 K) demonstrating a phase noise of -61 dBc/Hz at an offset of 10 kHz as measured at the operating frequency of 3·1 GHz (it is noted that this represents an upper bound that is limited by the available test equipment), which compares favourably with the work of others (Klieber 1992; Shen *et al.* 1993). The measured phase noise, normalised to dBc/Hz and to the centre frequency, is shown in Fig. 12 and compared with the output from a high stability synthesised microwave source for comparison.

It has been previously demonstrated that the centre frequency of an HTS resonator can be influenced by an externally applied magnetic field (Jenkins *et al.*

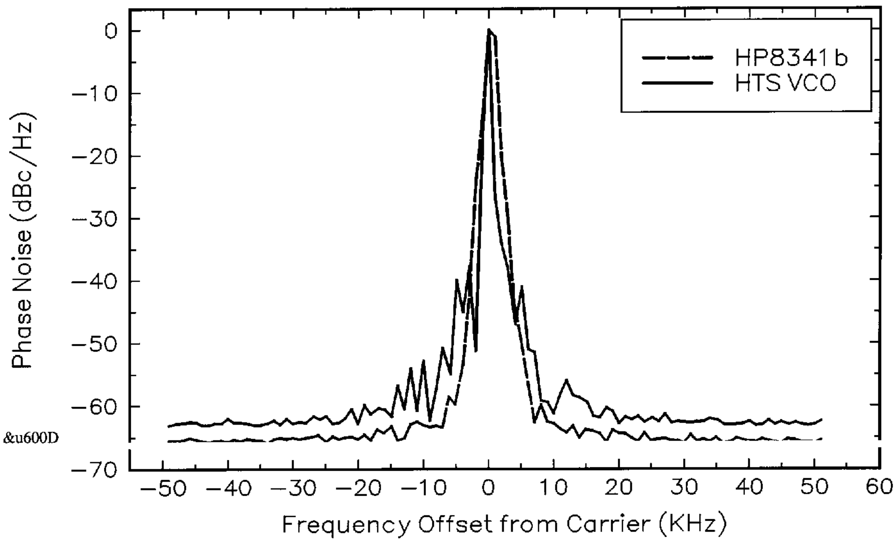

Fig. 12. Phase noise of the 3 GHz oscillator, compared with that of a Hewlett–Packard HP8341b synthesiser.

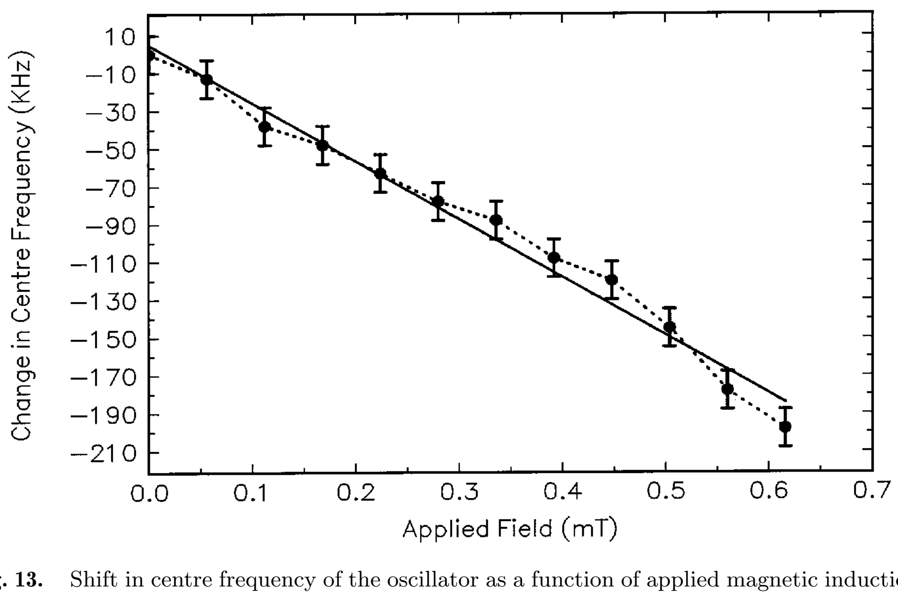

Fig. 13. Shift in centre frequency of the oscillator as a function of applied magnetic induction.

1993*c*). A voltage controlled oscillator can be implemented using this effect. The oscillator frequency changes linearly with the application of a small magnetic field; 0·5 mT produces a change of 200 kHz in the centre frequency, as can be seen in Fig. 13 (Jenkins *et al.* 1995*b*).

5. Conclusions

The feasibility of passive superconducting microwave devices and circuit components, implemented in HTS thin films and giving superior performance to copper, has been amply demonstrated. The logical next step in the development of HTS technology is towards fully integrated subsystems, complete receiver and transmitter front ends, and including active devices and cryocooler assemblies. This has in some part been achieved in demonstrators developed by various consortia. These developments have included a 35 GHz down converter (Forse and Rohlfing 1994), a low noise hybrid down converter operational at 7·4 GHz (Javadi *et al.* 1994) and a digital instantaneous frequency measurement subsystem incorporating HTS delay lines (Liang *et al.* 1994). Less conventional devices, such as an optically switched filter bank (Fenzi *et al.* 1994) and a direct sequence spread spectrum correlator (Jenkins *et al.* 1993*a*, 1994), are also being developed. There would therefore appear to be a considerable commercial future for HTS in microwave devices and systems. No less than five US companies demonstrated cellular base stations incorporating HTS components at the IEEE MTT-S International Microwave Symposium in San Francisco in June 1996!

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