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Possible High-Frequency Cavity
and Waveguide Applications of
High Temperature Superconductors

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ABSTRACT

Conventional superconducting materials used at liquid helium temperatures have been employed to greatly reduce ohmic power loss in microwave cavities. If suitable high temperature superconductor surfaces can be developed, it could be possible to alleviate constraints due to relatively low energy gaps and limits due to critical fields, and operate at more convenient temperatures with larger thermal margins. These features could be used to improve performance of present superconducting microwave cavity devices. They may also facilitate new applications and device designs at millimeter-wave and far infrared frequencies. Possible cavity and waveguide applications are described. Sensitivity of RF surface resistance to boundaries and nonaligned grains in the material and to small amounts of nonsuperconducting material may be an obstacle to development. Moreover, critical RF fields can be limiting for high power applications. An additional problem is the adverse effect of D.C. magnetic fields.

1. Introduction

Ohmic power loss can be a major limitation in cavities and waveguides in the microwave/far infrared frequency range. Conventional superconducting materials have been used to greatly reduce this loss in ultra high Q microwave cavities.¹ However, there are significant penalties resulting from operation of these cavities at liquid helium temperatures. Moreover, operation at high frequencies is limited by effects of relatively low energy gaps.

If suitable high temperature superconducting materials^{2,3} can be developed, it could be possible to alleviate constraints due to relatively low energy gaps and critical field limits and to operate at more convenient temperatures with greater thermal margins. These features could be employed to achieve improved performance from present microwave devices that use superconducting materials. They could also lead to new applications in the millimeter-wave/far infrared frequency range. In this paper we discuss possible implications of high temperature superconductors for cavity and waveguide operation and describe possible applications.

2. Energy Gap and Surface Resistance

The surface resistance of low temperature superconductors described by the BCS model will change from a very low value to a normal conducting value at photon quantum energies that are sufficient to split a Cooper pair. This photon energy is

$$E_{\text{PHOTON}} = 2\Delta(0) \approx 3.5 kT_c \quad (1)$$

where $\Delta(T/T_c)$ is the superconducting energy gap which depends on the ratio of T, the operating temperature to T_c , the critical temperature. For niobium with a critical temperature of 9.5K, $2\Delta(0)/h \approx 700\text{GHz}$. Photons with energies that are less than $2\Delta(0)$ can cause transitions to the normal state at nonzero temperatures and magnetic fields. Thermal excitation can also cause transitions to the normal state and increase the surface resistance.

Use of high temperature superconductors should alleviate the constraints provided by the relatively small energy gaps of conventional low transition temperature superconductors. If there were, in fact, a small energy gap in the new high transition temperature materials, thermal excitation of electrons across the gap should cause a transition to a normal state at a low transition temperature. The high transition temperature implies the absence of this limitation. Operation at much higher frequencies should thus be possible. Crudely, if there is a pairing energy and associated energy gap in the high temperature superconductors that scales with critical temperature, then materials with a critical temperature of $\sim 90\text{K}$ could have an order of magnitude larger energy gap than niobium (and about five times greater than Nb_3Sn). This increase, combined with a much larger temperature range, could facilitate robust operation at frequencies much higher than presently possible.

In conventional superconductors, the surface resistance increases with increasing frequency even when the photon energies are very low relative to the gap energy. This increase with frequency can be described with a two fluid model of superconductivity where there is resistive loss due to the presence of normal electrons provided by thermally induced transitions across the gap. For photon energies very much less than the gap the surface resistance can scale as^{1,4}

$$R_s \sim \frac{f^2}{T} \exp\left(\frac{-\Delta(T/T_c)}{kT}\right) + R_0 \quad (2)$$

where f is frequency and R_0 is residual resistance (which could result from nonsuperconducting surface area). Since the surface resistance increases with reduced gap energy, the absence of relatively low gap energies could also be used to compensate for the f^2 dependence of R_s and facilitate high frequency operation.

Use of higher frequencies may allow higher electric fields due to reduced multipactoring and field emission electron loading.⁵

In addition, the high critical magnetic field in high temperature superconductors may facilitate operation over a much wider range of conditions than is possible with low temperature superconductors. Higher

RF magnetic fields may be permitted, allowing operation with higher power densities and electric fields.

3. Cavities

a) Microwave Cavities

Microwave cavities using low temperature superconductors have been employed as particle accelerators, oscillators, filters, and other applications.¹ The use of superconducting material greatly decreases power loss and provides a very high value of the cavity quality factor Q . Q values of 10^{11} have been obtained.

Q is related to surface resistance by

$$Q \sim \frac{\Gamma}{R_s} \quad (3)$$

where Γ is a geometry factor. For room temperature copper at 3 GHz, $R_s \approx 10^{-2}$ ohms. Typical geometry factors are $\Gamma \sim 200$ ohms and values of Q are $\sim 2 \times 10^4$. R_s can be reduced by 10^6 by using superconducting niobium cavities resulting in $Q \approx 2 \times 10^{10}$.

The power lost by ohmic heating of the walls, P scales as

$$P \sim \frac{E^2 f}{Q} \quad (4)$$

where E is the electric field in the cavity. Very high Q superconducting cavities are used to maintain power loss at acceptable values in RF accelerators that have very large electric fields. As mentioned previously, operation with conventional low temperature superconductors is limited by a number of constraints. Use of high temperature superconductors might make possible operation at substantially more convenient temperatures, higher electric fields, and higher values of Q .

b) Millimeter-Wave/Far Infrared Cavities

Operation of millimeter-wave cavity devices using normal conductors can be significantly constrained by high wall loading even when very high electric fields are not required. The wall loading scales as

$$P_W \sim \frac{E_{RF}^2}{QA} \sim \frac{E_{RF}^2 f^3}{Q} \quad (5)$$

where the wall area, A, scales as $A \sim f^2$ for fixed mode number. Use of high temperature superconductors in millimeter-wave/far infrared cavity devices could be important in alleviating wall loading constraints and/or making possible very high values of Q.

c) Coatings

Uniform superconducting properties are needed over the entire cavity surface. Since the currents induced by the electromagnetic radiation are highly localized, the presence of even a small amount of non-superconducting surface area could drastically increase the surface resistance. Moreover, the surface resistance may be very sensitive to boundaries and grain alignment of the superconducting materials. Special thin film coating approaches may be required. For materials with anisotropic superconducting properties like Y-Ba-Cu-O, it may be advantageous for the Cu-O planes to be deposited parallel to the surface of the cavity.⁶

d) Cooling

Steady state helium gas cooling might be used over a wide range of temperatures between liquid nitrogen temperature and liquid helium temperature. Operation at temperatures well below T_c may be necessary to obtain a sufficiently low value of $\exp(-\Delta/T)$ in the expression for surface resistance in (2). Steady state liquid nitrogen cooling could be employed if the properties of the superconductor at 70-80K are acceptable. The advantage of liquid nitrogen cooling is that large amounts of heat can be removed at relatively high efficiencies. Other

cooling fluids such as Ne and H might also be used. For some applications the cooling would occur in back of the substrate on which the superconductor is deposited, requiring good thermal conductivity through the substrate. In other applications gas cooling might be applied directly to the front phase of the superconductor.

4. Gyrotron Cavities and Mode Convertors

a) Effect of Reduced Ohmic Losses

A possible high frequency superconducting cavity application is in high power gyrotrons.⁷ The gyrotron produces high power millimeter-wave radiation by bunching of an electron beam in a copper resonant cavity subjected to a magnetic field.⁸ When the electron cyclotron resonance frequency is approximately equal to characteristic frequency of the cavity, energy can be transferred from the beam to cavity radiation (for 140GHz the D.C. magnetic field for first harmonic operation is ~5 T). Cavity wall loading can be the dominant limitation on the amount of power that can be produced in a CW device, particularly in high frequency (>100GHz) tubes which use compact cavities in order to provide a sufficiently thin mode spectrum for operation in a desirable single mode.

This constraint might be alleviated by use of a high temperature superconductor resonator. Even if the superconducting resonator wall material has a relatively high surface resistance and an ultra high Q is not attained, a large increase in conductivity relative to copper could substantially reduce the wall loading and increase the allowed gyrotron power output. ($Q_{\text{ohmic}} \sim a/\delta \sim a^{1/2} \sigma^{1/2}$, where a is the cavity radius, δ is the skin depth and σ is the conductivity.) For example, an increase in σ by 100 times relative to copper would reduce the wall loading by a factor of ten.

However, the presence of the large D.C. magnetic field in the gyrotron resonator could drastically increase the surface resistance of the superconductor, resulting in a low value of Q_{ohmic} . (This has been observed in present microwave cavities.⁹) Experimental determinations of the millimeter-wave/far infrared surface resistivity of high

temperature superconductors in this environment are critical for this application.

A schematic drawing of a gyrotron resonator is shown in Figure 1. Its dimensions would depend on the frequency and mode of operation. A TE_{03} , 140GHz resonator would have an internal diameter of 7mm.

b) Mode Convertors

Mode convertors¹⁰ are generally required to convert source (e.g. gyrotron) output to a linearly polarized beam peaked on axis. Such spatial beam qualities are necessary for many applications including electron cyclotron resonance heating in plasmas, plasma diagnostics, and possible application to radar and communications. Keeping the resonator dimensions as small as possible with superconducting materials will facilitate mode convertor design by minimizing source output mode order.

Use of superconducting materials in the waveguide mode convertors themselves can also lead to significant improvements. Eliminating or reducing the ohmic losses in these convertors would make possible very compact designs at high frequencies. Efficiencies would be improved not only because of lower ohmic losses, but also because mode conversion to unwanted higher order modes would be reduced with smaller guide dimensions. Peak power handling capabilities could be maintained by including the compact convertors in the high vacuum system of the gyrotron.

An illustrative design for a superconducting symmetric mode, TE_{on} \rightarrow TE_{on} circular guide mode convertor, is shown in Figure 2. Figure 3 shows a design for a $TE_{01} \rightarrow TE_{11}$ convertor.

The use of quasi-optical mode convertors could also be facilitated with superconducting gyrotron resonators. Quasi-optical mode convertors have been shown to work well in transforming gyrotron radiation generated in whispering gallery modes, TE_{mp} , where $m \gg 1$ and $p = 1$. Gyrotron operation in such modes is also advantageous for minimizing mode competition since the electron beam is propagated near the surface of the resonator and does not excite the more closely spaced

volume modes. However, whispering gallery modes have ohmic losses with conventional conductors that make such gyrotrons impractical at very high frequencies. Ohmic Q is given as

$$Q_{\text{ohmic}} = \frac{a}{\delta} \left(1 - \frac{m^2}{v_{mp}^2}\right)$$

where v_{mp} is the p th zero of the J'_m Bessel function, and m and p are the mode indices. High temperature superconducting materials could improve prospects for this type of gyrotron in the submillimeter-wavelength range by significantly decreasing the skin depth δ to offset small radius and large m number.

5. Accelerators and Free Electron Lasers

The main application of present superconducting cavities is in high duty factor RF particle physics accelerators with ultra high values of Q (on the order of 10^{10}). Use of high temperature superconductors could substantially reduce cryogenic systems costs by higher temperature operation and might facilitate operation at high frequencies. Reduced size due to higher acceleration gradients of higher frequency operation might also be possible.

Improved superconducting RF accelerators could also be of use in free electron lasers. Another application could be the development of electromagnetic wave wigglers using millimeter-wave cavities.¹¹

6. Waveguides and Other Transmission Systems

Superconducting waveguides could also be developed using the approaches described above. This could be useful in the millimeter-wave range where present copper fundamental mode guides are very lossy. Low order mode operation in overmoded guide is usually employed to reduce ohmic losses. Overmoded operation, however, has the disadvantages of the possibility of mode conversion leading to increased loss and dispersion. Prevention of mode conversion can constrain tolerances and increase the difficulty of implementation since unplanned bends must be avoided. WR-7

fundamental waveguide for transmitting 110-170GHz has rectangular dimensions of 1.65 x 0.81mm with conventional conductor losses of 6dB/m at 140GHz. At higher frequencies dimensions become smaller and ohmic losses are more severe. The performance of these guides would be substantially improved by using superconducting coatings. The power loss for a given waveguide scales directly with the surface resistance. Thus improvements of orders of magnitude in power loss could be in principle possible.

Dispersion in fundamental waveguides can constrain allowed bandwidth and limit some applications. Moreover, as frequency increases, construction of fundamental guide becomes more difficult. Superconducting overmoded guides may be useful for very high frequency operation (>200GHz) where losses can be significant even for low order modes. Dispersion can be low for low order modes in overmoded guides if mode conversion is controlled. The absence of low energy gaps should make possible operation at frequencies greater than 1 Terahertz. As a rough estimate, scaling the energy gap according to (1) leads to a projected gap frequency >5Thz for a critical temperature of ~90°K.

The development of waveguides using superconducting coatings could facilitate the use of millimeter-wave communications with its advantages of high bandwidth and very sensitive receivers. Use of these guides could also significantly improve the front end performance of millimeter-wave receivers used in radar, communications, and radio astronomy.

Figure 4 provides an illustrative design for a rectangular superconducting millimeter waveguide. Circular waveguides could also be developed. The rectangular waveguide configuration could have the advantage that it might be easier to coat single crystal films on it. One possible approach for cooling would be to use helium gas inside the guide to serve the dual function of cooling and preventing absorption of millimeter-wave radiation.

Other types of transmission systems, such as striplines, could also benefit from the capability of much higher frequency operation (>1 Terahertz).

7. Conclusions

A variety of microwave/far infrared resonator and waveguide components might be developed with high temperature superconductivity materials. These relatively small scale applications do not require thick materials, electrical contacts, special materials interfacing as in semiconductor devices, or special structural support. However, there are a number of obstacles that may inhibit their development. The RF surface resistance can be severely affected by boundaries, random grain alignment, and the presence of nonsuperconducting material. As far as we know, low surface resistance to high frequency electromagnetic radiation has not yet been observed in experiments with high temperature superconducting materials. Moreover, critical RF magnetic fields can be limiting for high power applications. An additional problem is the adverse effect of D.C. magnetic fields.

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Figure Captions

Drawings are not to scale.

- 1a) Cross section of superconducting gyrotron resonator; 1 – superconducting coating, 2 – substrate for superconducting coating having good thermal conductivity, 3 – coolant jacket, 4 – optional baffles inside coolant jacket to insure uniform coolant flow, 5 – extension of coolant jacket beyond ends of superconducting component to insure uniform cooling and provide interface for input and output components.
- 1b) Three dimensional view of the superconducting gyrotron resonator showing cylindrical symmetry.
- 2a) Cross section of a superconducting symmetric mode, $TE_{on'} \rightarrow TE_{on}$, circular guide mode convertor. The guide has an axisymmetric sinusoidal internal diameter ripple given by

$$a(z) = a[1 + \eta \sin(\frac{2\pi}{L} z)]$$

where a is the mean radius, η is the relative ripple amplitude, L is the beat wavelength between the $TE_{on'}$ and TE_{on} modes, and z is the position along the length of the convertor. The definition of the number labels is the same as for Fig. 1a.

- 2b) Three dimensional view of the superconducting $TE_{on'} \rightarrow TE_{on}$ circular guide mode convertor showing cylindrical symmetry.

- 3a) Cross section of a superconducting $TE_{01} \rightarrow TE_{11}$ circular guide convertor. This convertor has a wriggle or snake-like deformation of the convertor axis of the form

$$y = a\eta \sin\left(\frac{2\pi}{L} z\right)$$

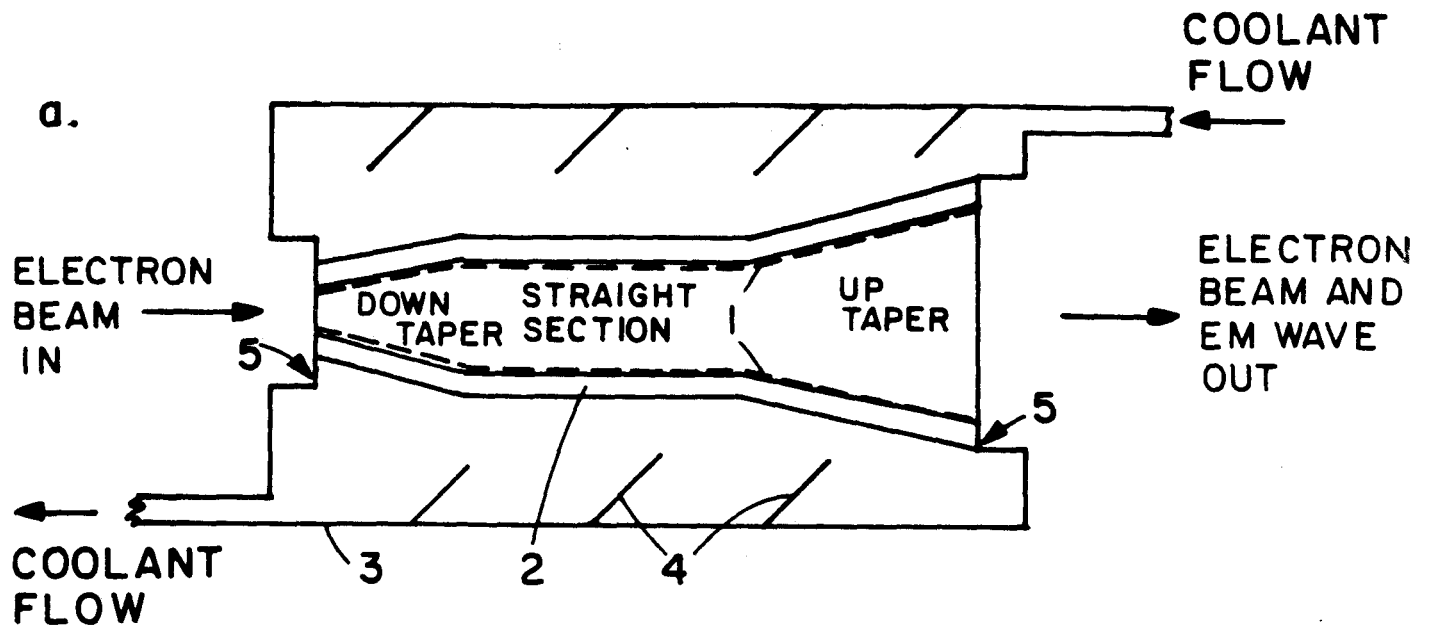
where y is the deviation of the axis, a is the internal guide radius, η is the amplitude of the deformation, L is the beat wavelength between the TE_{01} and TE_{11} modes, and z is the position along the axis. The input and output ends are not parallel to each other because the convertor is an odd multiple of $1/4$ wavelengths long. Choosing such a length improves conversion efficiency by suppressing the competing TE_{21} mode. The number labels are the same as in Fig. 1a.

- 3b) Three dimensional view of the superconducting $TE_{01} \rightarrow TE_{11}$ wriggle mode convertor showing its cylindrical symmetry.
- 4a) Cross section of a superconducting millimeter waveguide. A straight waveguide section is shown here. However, many other millimeter-wave components such as bends, waveguide transitions, power dividers, etc., could be coated with superconducting material and enclosed in a coolant jacket similar to the straight guide shown here.

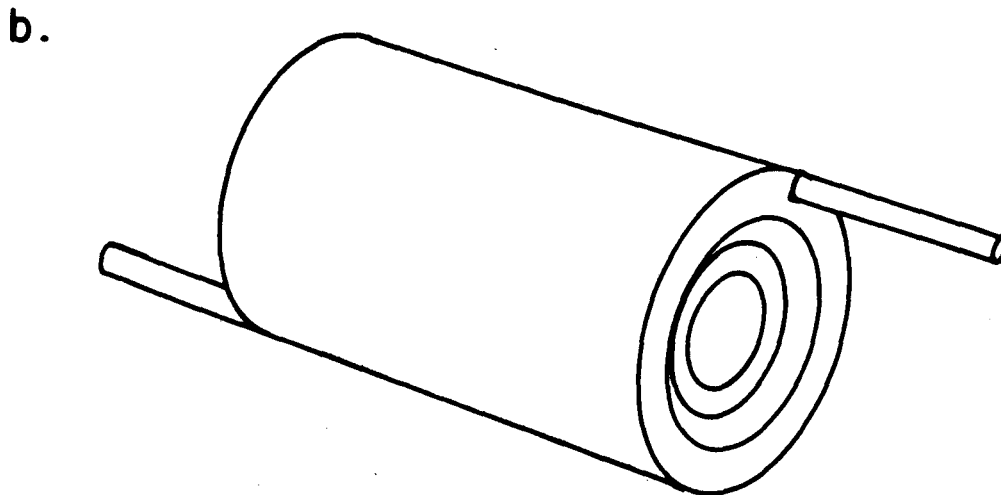
Numerical labels 1 through 5 are the same as for Fig. 1a., 6 – flange, 7 – alignment pins.

- 4b) Three dimensional view. A rectangular guide is shown, but it could be circular as well.

SUPERCONCONDUCTING GYROTRON RESONATOR



CUT AWAY VIEW

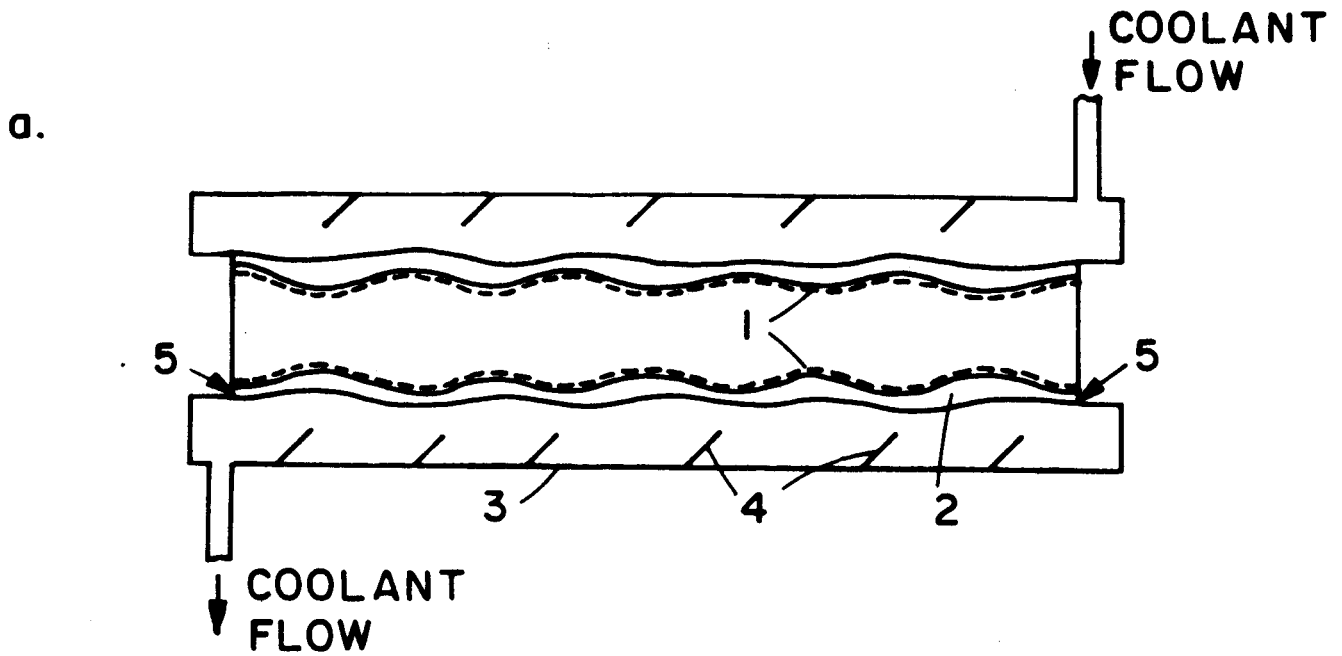


3- DIMENSIONAL OUTSIDE VIEW

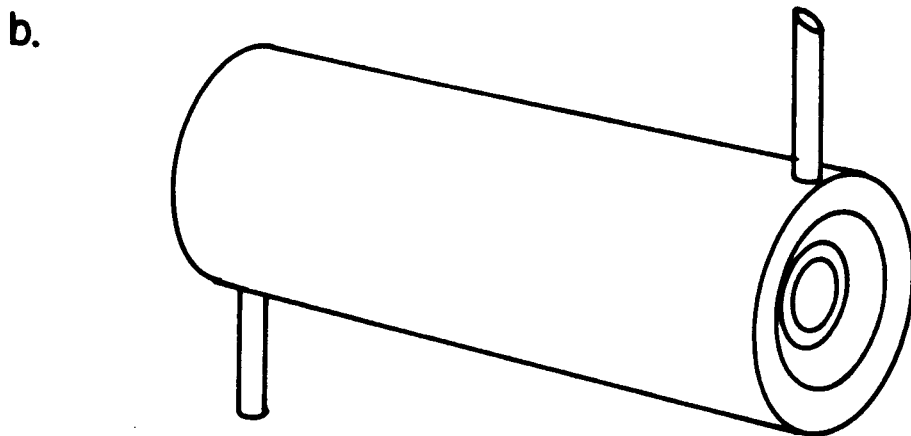
FIG. 1

SUPERCONDUCTING

$TE_{0n}' \rightarrow TE_{0n}$ CIRCULAR WAVEGUIDE MODE CONVERTER



CUT AWAY VIEW

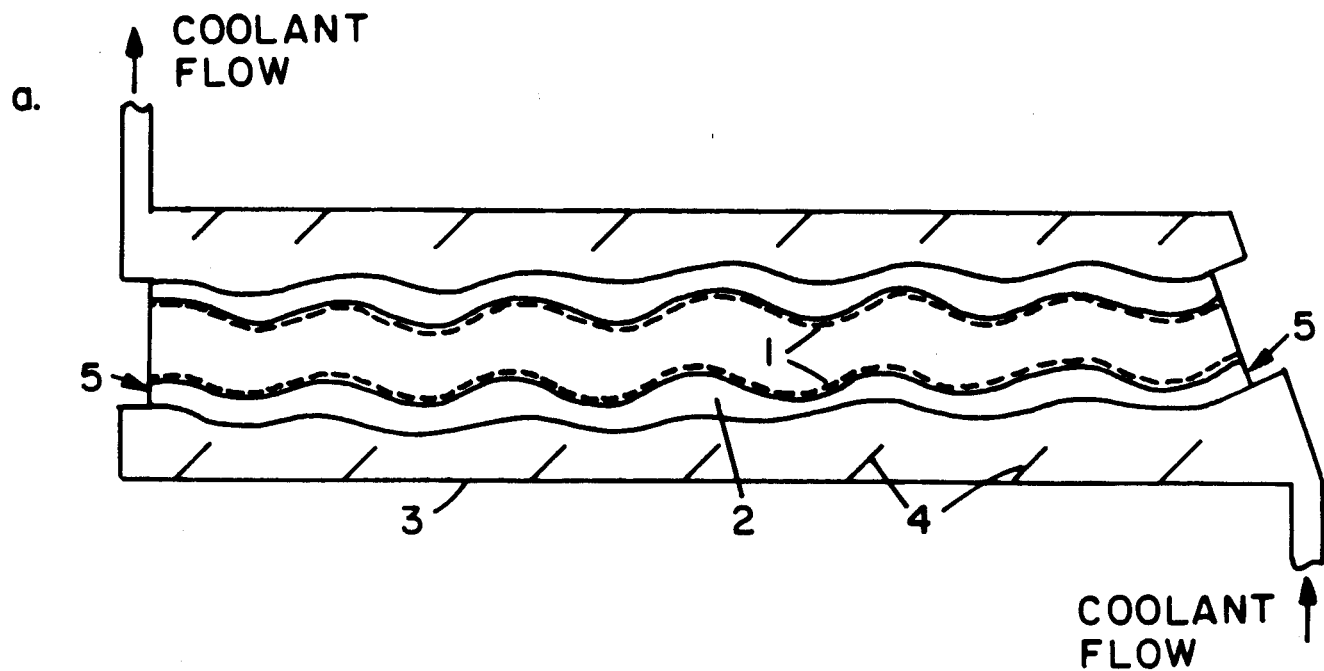


3 - DIMENSIONAL OUTSIDE VIEW

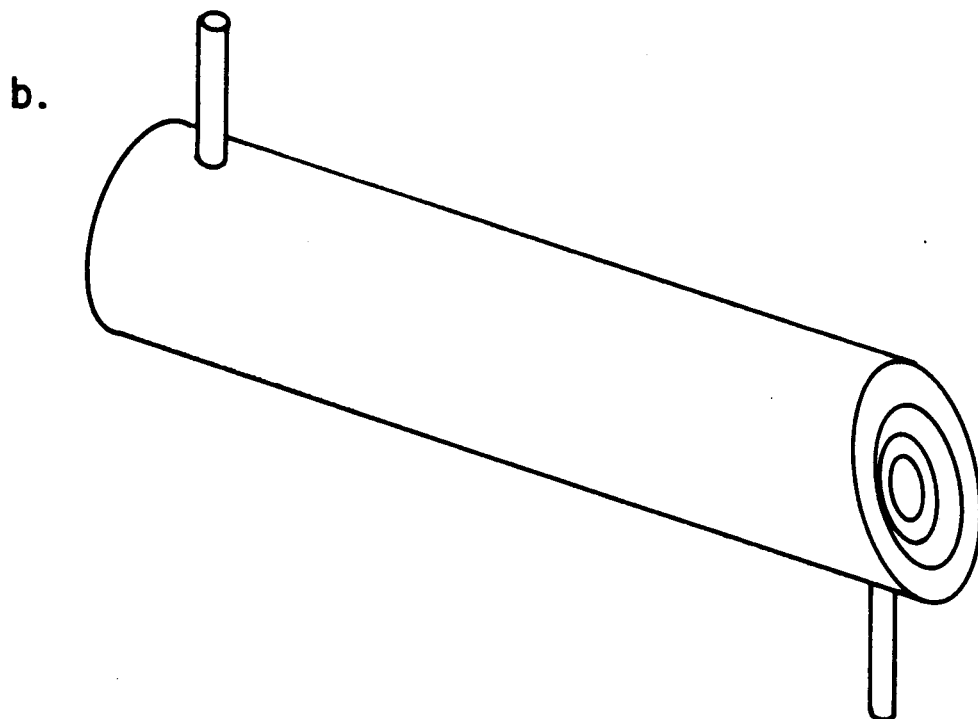
FIG. 2

SUPERCONDUCTING

$TE_{01} \rightarrow TE_{11}$ CIRCULAR WAVEGUIDE MODE CONVERTER



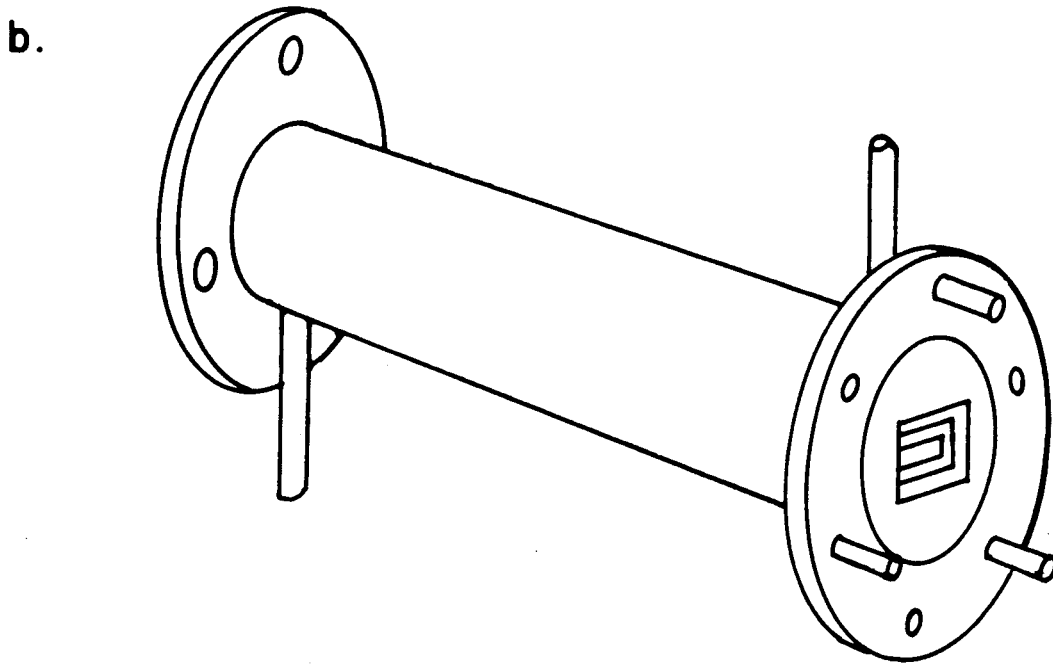
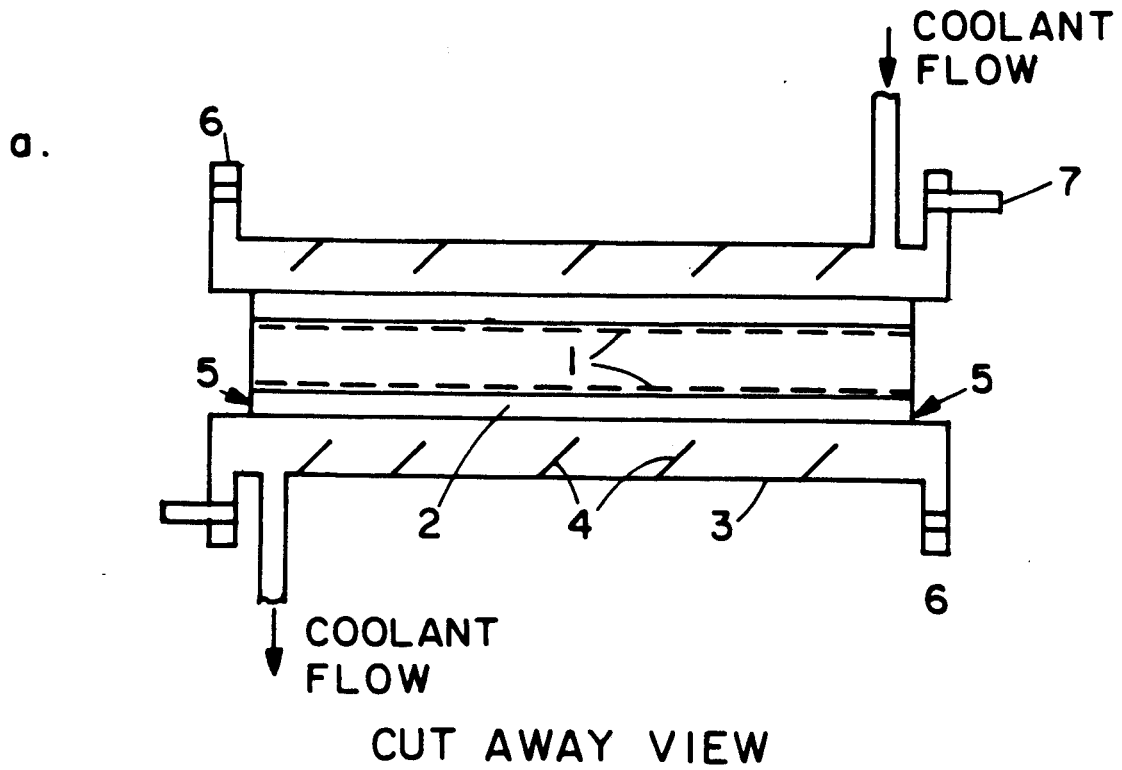
CUT AWAY VIEW



3-DIMENSIONAL OUTSIDE VIEW

FIG. 3

SUPERCONDUCTING MILLIMETER WAVEGUIDE



3-DIMENSIONAL OUTSIDE VIEW

FIG. 4