N67 12313

The Travelling Wave Maser Amplifier in the Goonhilly Radio Station*

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The design and performance of the 4170 Mc/s travelling wave maser at present installed at the GPO Radio Station, Goonhilly Downs, is described. Means of increasing the bandwidth of the device are discussed.

AUTHOR

SYSTEM REQUIREMENTS AND MASER SPECIFICATION

The signal entering the first stage of the Goonhilly receiver is very small, about 10^{-12} watts, and the bandwidth of the system is some tens of megacycles. If the received signal is to be amplified and detected with an acceptable signal to noise ratio then it is essential that the noise contribution made by the first stage amplifier should be as small as possible. It was therefore decided that the first stage amplifier should be a solid state travelling wave maser (TWM) having sufficient net gain to make the noise contribution of the second stage amplifier insignificant. The specification for this TWM is as follows:

Signal Frequency	4170 Mc/s
Gain (minimum)	20 db
Bandwidth to 3 db points	25 Mc/s
Noise temperature	15°K
Input VSWR	0.666 over the operating band
Operating life per filling of liquid helium	8 hrs.

DESIGN OF THE MASER

The overriding consideration in the design of this maser was the need to produce an engineered and operating device within some six or seven months of the initiation of the project. Sophistication in the

* First published by the Institute of Electrical Engineers, November 1962.

design therefore was subordinate to expediency and as far as possible use was made of immediately available materials and techniques.

Active Materials

Because of its ready availability in large single crystals and also because of its proven characteristics synthetic ruby was selected as the active material. Previous experience indicated that the best orientation for maser operation at frequencies below 7 kMc/s is that in which the applied magnetic field is at right angles to the c-axis of the ruby. In this orientation the ground state of the Cr^{3+} ion is split by the combined action of the crystal fields and the applied magnetic field according to the energy level diagram of Fig. 1.

It has been found experimentally that when the separation of levels 1 and 2 corresponds to a frequency of 4170 Mc/s the greatest inversion of the populations of these levels can be obtained if the pump is applied between levels 1 and 4, i.e., at a frequency of 30,150 Mc/s. In ruby having a Cr to Al ratio of 0.05 atoms per cent we find that 1-4 pumping produces an inversion ration of 2.7 at 1.4°K.

Operation at 1.4°K involves reduction of the liquid helium bath pressure to about 2.5 mm Hg. In practice this is accomplished within less than half an hour of filling and in an experimental system such as this where operation over more than three successive satellite passes is rarely required this is no disadvantage.

Assuming that the excitation at the signal frequency is by an RF magnetic field circularly polarised in the plane perpendicular to the applied field (a condition which is closely approximated in practice) and using the table of transition probabilities prepared by Chang and Siegman[3] we calculated by the method outlined[2] that 1-4 pumping in 0.05% ruby at 1.4°K will produce a value of Q_m of $-15/\eta$. Q_m is the magentic quality factor of the structure and is essentially a measure of the ratio of the energy stored in the structure to the power absorbed by the maser material, η is the filling factor of the maser and is the ratio of the mean square RF magnetic field over the volume of the maser crystal to that over the volume of the propagating structure. Although filling factors up to 0.5 are theoretically possible in a TWM experience suggests that 0.2 is a practical figure. Taking $\eta = 0.2$ we have $Q_m = -75$ as a basis for design.

Non-Reciprocity

A travelling wave maser exhibits some non-reciprocity by virtue of the fact that circularly polarised field of opposite sense interact to

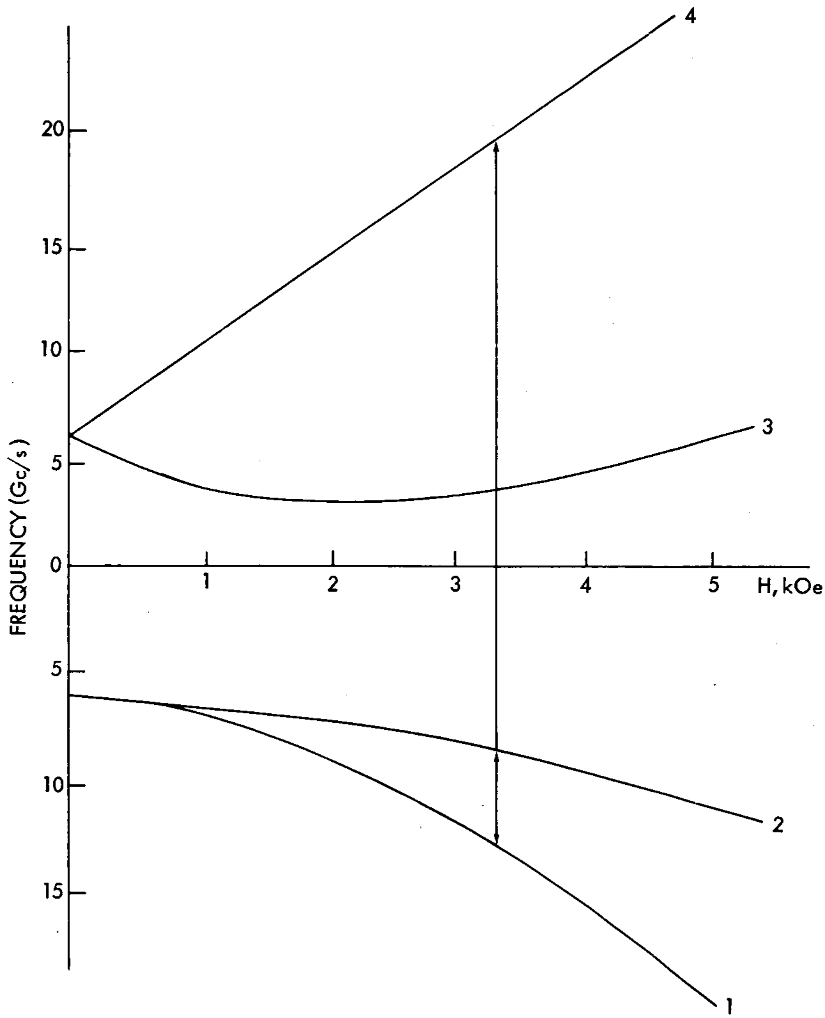

Fig. 1 — Energy level diagram (Ruby, $\theta = 90°$).

different extents with the active ions[4]. However, additional non-reciprocal backward loss must be provided if a completely stable device is to be obtained. Polycrystalline yttrium iron garnet is a suitable material for this purpose as its absorption line width is reasonably narrow (about 150 oersteds) even at liquid helium temperature. Because of its high susceptibility only a small volume of this material needs to be incorporated in the maser. The dimensions of the yttrium iron garnet (YIG) are adjusted in order that resonant interaction at the signal frequency can be obtained with the same applied field as is required to give the correct ruby energy level splitting. In the present case the field is 3,280 oersteds and an appropriate shape for the YIG is a flat disc of aspect ratio 0.1 with the plane of the disc perpendicular to the applied field.

Obviously it is necessary that the YIG discs should be incorporated in the TWM in such a way that they are acted upon by a substantially circularly polarised RF field of opposite sense to that acting upon the ruby. This is accomplished by making use of a comb slow wave structure as described in the following section.

Slow Wave Structure

The small signal gain of a TWM can readily be expressed in terms of two quality factors, Q_m the magnetic Q discussed above and Q_0 the intrinsic Q of the propagating structure determined by ohmic and dielectric losses and also the forward loss of the YIG. If r is the slowing factor (the ratio of the group velocity in the propagating structure at the signal frequency to the free space velocity of light) and N is the number of free space wavelengths in the structure the net gain of the device, expressed in db is

$$G = 27.3\, rN \left(\frac{1}{Q_m} - \frac{1}{Q_0}\right).$$

A structure having a slowing factor of 100 and an active length of 1.6 free space wavelengths (which is a convenient figure at a frequency of 4170 Mc/s) will therefore give an electronic gain of 58 db if $Q_m = -75$.

A suitable slow wave structure for the TWM is then one having this slowing factor and containing regions in which the RF magnetic field is circularly polarised, the structure must also be such as to allow propagation of the pump frequency, not necessarily in a slow mode.

All these requirements can be met by structures consisting essentially of an array of parallel conductors in which the RF magnetic field is substantially circularly polarised, the senses of polarisation on the two sides of the array being opposite.

A comb structure[1, 5] is used in the present maser and has dimensions as indicated in Fig. 2, the positioning of the ruby, dielectric and YIG discs in the structure is apparent from this figure.

The dispersion characteristic for this structure when containing liquid helium is similar to that shown in Fig. 3, and the slowing factor

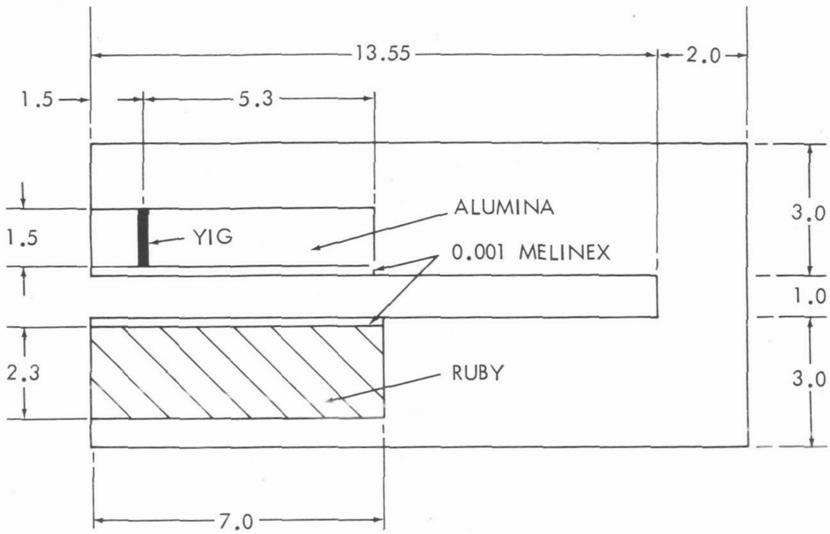

Fig. 2a — Cross-section of the 4170 Mc/s comb structure.

at the signal frequency is 110. The comb is milled from a block of high conductivity copper, this form of construction tending to minimize conductor losses. (The slowing factor of 110 quoted above was inferred from the observed pass band of the structure, subsequent measurements of the $\omega\beta$ characteristic of a similar comb suggest that this is over-estimated by about 10%.)

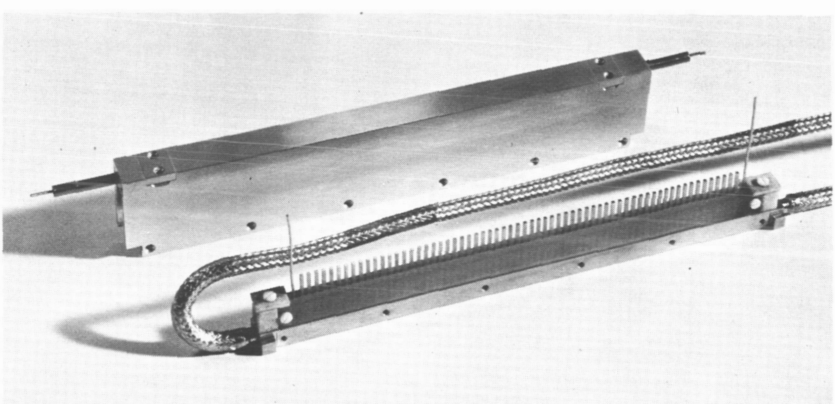

Fig. 2b — The comb structure.

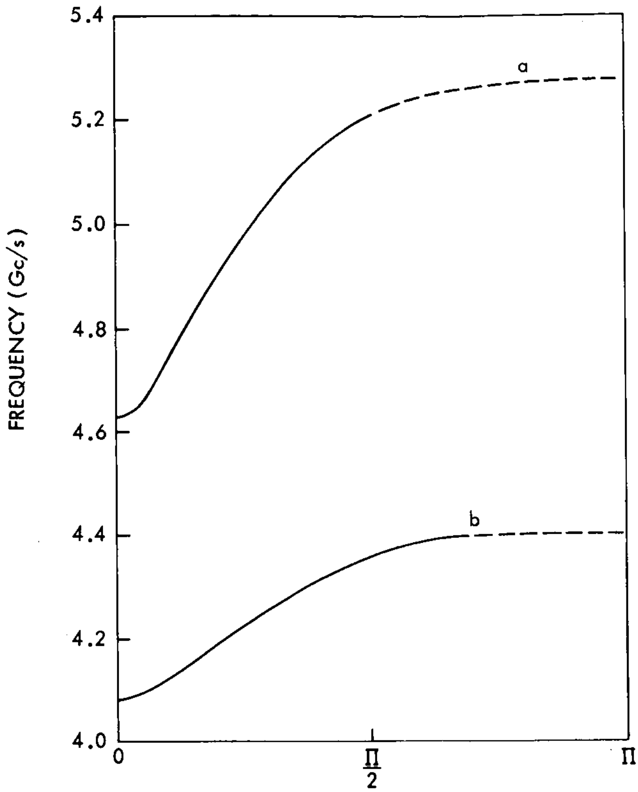

Fig. 3 — Phase change per conductor.

Input Leads

The input and output leads to the maser are air dielectric coaxials of low thermal conductivity (silver plated copper nickel). The leads have an outside diameter (od) of 15 mm and a characteristic impedance of 72 ohms. It is important that these leads have a low electrical loss as they make the main contribution to the maser noise temperature. At the cryostat head these leads terminate in vacuum sealed wave guide to coxial transitions. At their lower end the leads have tapered transitions to 5 mm od coaxials having *P.T.F.E.* dielectric. These latter coaxials are matched to the comb by means of the arrangement shown in Fig. 4. Some adjustment of the separation between the matching conductor and the first finger of the comb is

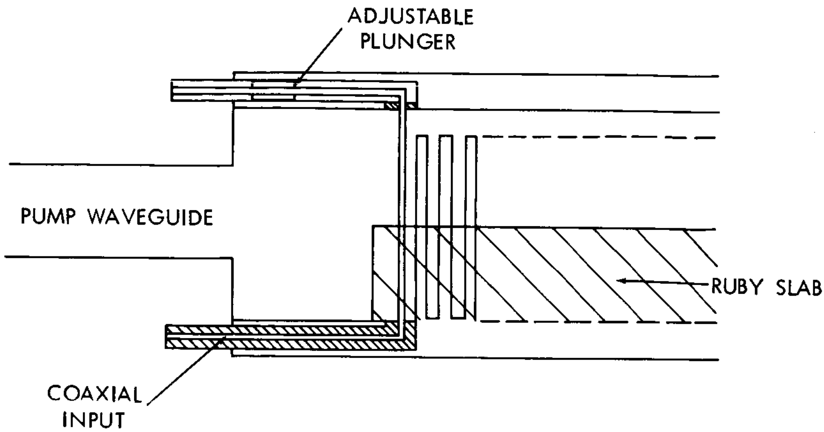

Fig. 4 — Schematic of matching unit.

necessary if the optimum match is to be secured over the pass band of the structure.

The pump power at 30,150 Mc/s is supplied by way of thin walled (0.2 mm) copper nickel waveguide with the internal dimensions of WG_{22}. Approximately 40 mW is required to saturate the pump transition, this output power is obtained from selected R9518 klystrons.

In this connection we may note that operation at 1.4°K calls for substantially less pump power than does operation 4.2°K and thus although, with a given pump source, pump frequency stabilization may be necessary for 4.2°K operation it is not necessary for 1.4°K operation. No pump frequency stabilization is provided in the present maser.

Maser Packaging

The final form of the maser package depends on the form of magnet used. Superconducting magnets by virtue of their light weight and very high stability are attractive for use with masers operating at liquid helium temperatures and at the outset of the development of the Goonhilly maser it was hoped to make use of superconducting magnets. It soon became apparent, however, that the construction of a superconducting magnet giving the requisite field homogeneity was a matter of some difficulty and in view of the short time available for development a permanent magnet version of the maser package was constructed as a parallel development. The permanent magnet version of the maser is illustrated in Fig. 5 in which the trimming coils used to adjust the field of the permanent magnet are clearly visible.

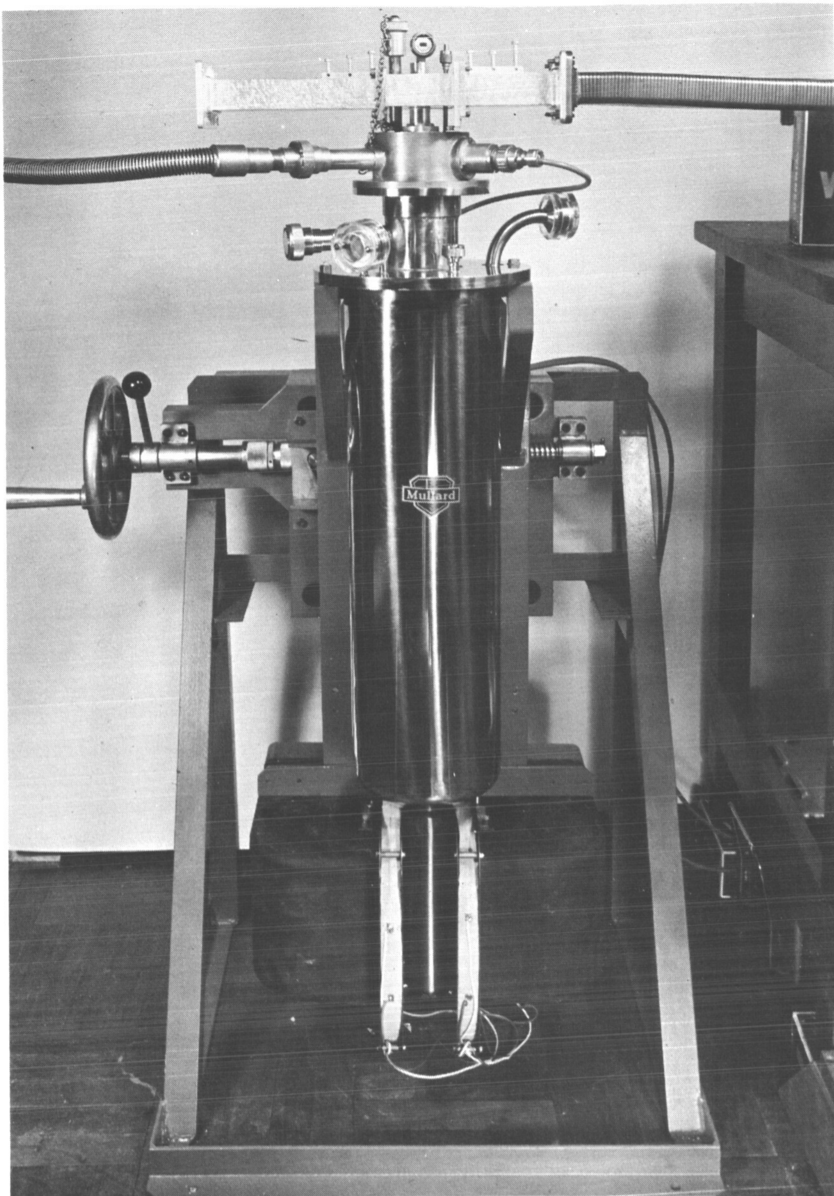

Fig. 5 — Maser package with permanent magnet.

Following the work of Cioffi[6] on the use of superconducting screens in magnetic circuits a superconducting magnet has been developed in which satisfactory operation of this maser in the laboratory has been obtained. Superconducting magnet masers have however not been employed in the Goonhilly system.

MASER PERFORMANCE

Laboratory Operation

In the permanent magnet shimmed to provide a field of 3280 oersted uniform to better than 0.1% over the volume of the ruby the maser gives in the laboratory the performance summarized as follows:

Operating temperature	1.4 °K
Electronic gain	50 db
Bandwidth to 3 db points	16 Mc/s
Field	3280 oersteds
Pump frequency	30, 150 Mc/s
Noise temperature	15 ± 4 °K
Isolator backward loss	60 db
Isolator forward loss	3 db
Structure loss	8 db
Net forward gain	39 db
Input VSWR	1.4
Operating life/filling of He	8 hrs.

Saturation effects become apparent at an input power of −65 dbm. The effect of possible breakthrough from the Goonhilly 6390 Mc/s transmitter on the maser performance was investigated in the laboratory and with the maximum power available (100mW) at this frequency incident on the maser the performance at 4170 Mc/s was unaffected, and subsequent site experience confirmed this.

The recovery time of the maser after saturation at 4170 Mc/s is 150 miliseconds.

Bandwidth

The specification bandwidth of 25 Mc/s is slightly greater than can be achieved in a TWM in a uniform magnetic field and giving a net gain in excess of 20 db (Fig. 6). This was realized at the outset of the project and the maser was therefore designed to give a higher gain

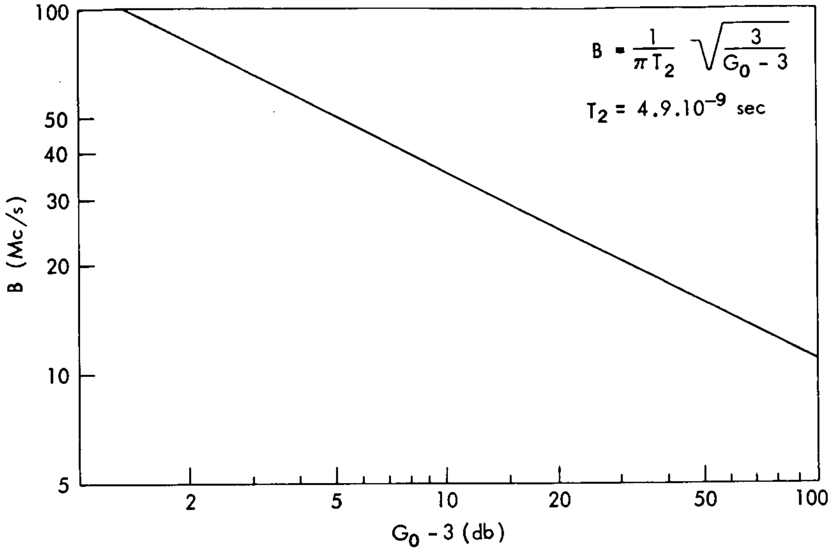

Fig. 6 — Bandwidth versus electronic gain (G_0) for TWM in a uniform field.

than the specified 20 db in a uniform field in order that ultimately the bandwidth could be increased for instance by field staggering. (Another reason why the maser was designed for high gain was that the operating temperatures which would be obtained at Goonhilly were uncertain in view of the considerable length of pipe between the maser and the helium pump—in the event 1.4°K was readily achieved.)

The bandwidth of a TWM can be increased in practice by staggering either the crystal orientation or the magnetic field along the length of the maser. Orientation staggering is however undesirable as it results in an unfavorable exchange of gain for bandwidth.

The bandwidth resulting from various forms of field staggering has been calculated on the assumption of a Lorentzian line shape and is plotted against peak electronic gain in Fig. 7. Clearly a substantial increase in bandwidth can be obtained by the simple expedient of introducing a step in the magnetic field by suitably shimming the magnet.

In Fig. 9 the observed gain of the maser is plotted against frequency for the case in which a step is introduced in the magnetic field by means of 0.006″ steel shims on the magnetic pole faces (magnet pole gap = 2.25″).

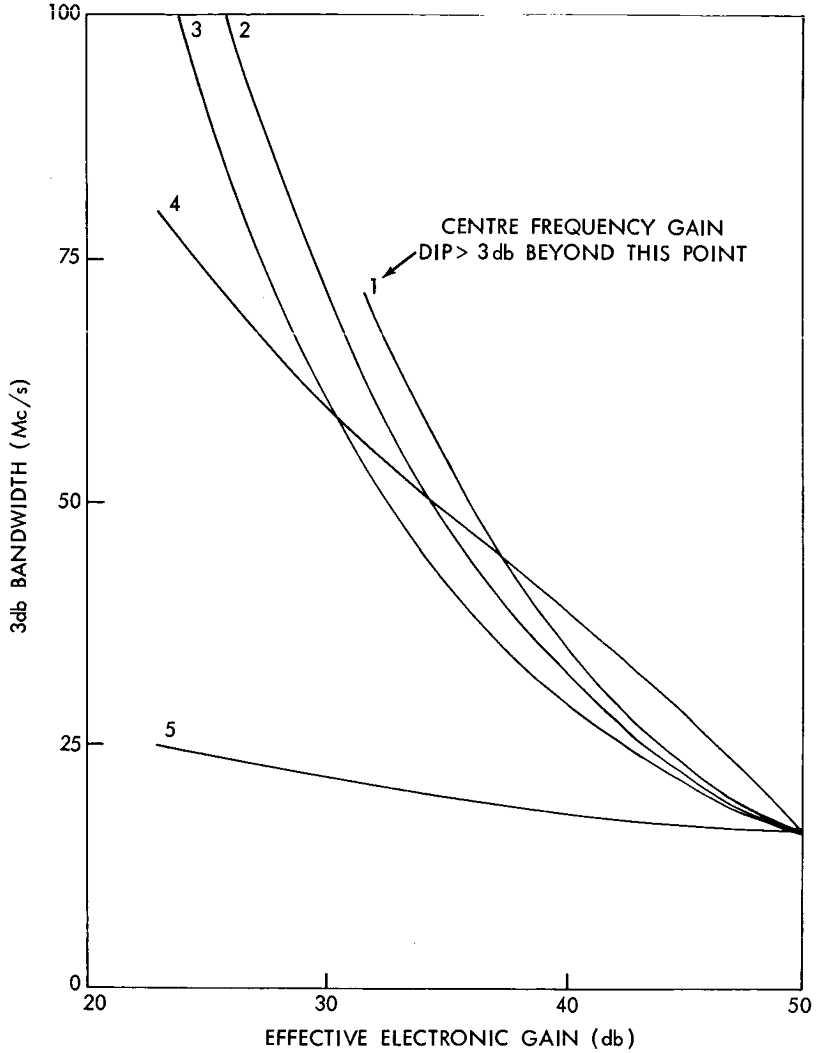

Fig. 7 — Bandwidth curves for maser with electronic gain of 50 db in uniform magnetic field with operating temperature 1.4°K and $T_2 = 5.10^{-9}$ sec: (1) Magnetic field variation—single step; (2) Magnetic field variation—sinusoidal; (3) Magnetic field variation—linear; (4) Gain equalisation; and (5) Operating temperature variation.

Site Operation

The uniform field permanent magnet version of the master was installed in the Goonhilly aerial in June, 1962 (Fig. 9) in a cabin at the back of the dish and gave a similar performance to that measured in the laboratory. It was, however, not possible to obtain consistently an operating life of eight hours per filling of liquid helium when operating at 1.4°K, this being presumably due in part at least to the continuous movement of the aerial during satellite tracking. Changes in elevation of up to 100° are possible and for this reason the maser is mounted at 45° to the vertical when the dish is pointing to the horizon (Fig. 6).

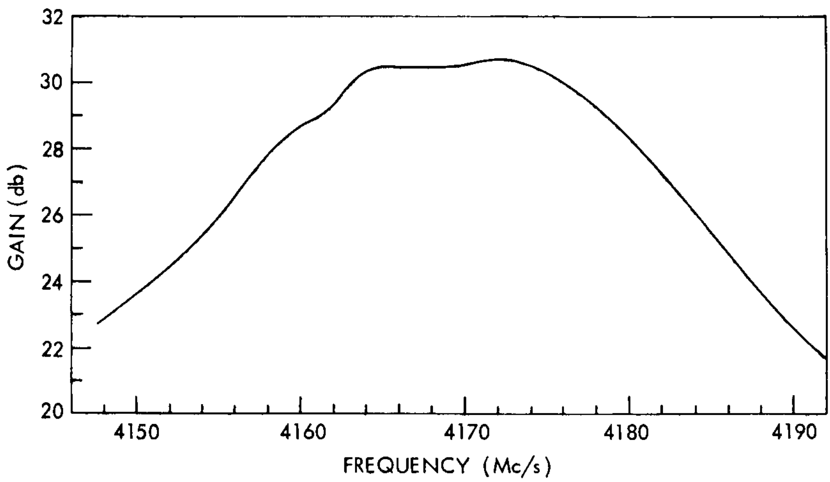

Fig. 8 — Net gain-frequency characteristic of broad-band maser.

Following the initial Telstar experiments which were carried out using the maser in a uniform magnetic field the bandwidth of the device was increased by shimming the magnet as described above. A further improvement made has been the replacement of the small helium dewar vessels illustrated in Fig. 5 by substantially larger vessels as shown in Fig. 10. The use of the larger vessel has increased the continuous operating time per filling of liquid helium from less than eight hours to about 2 days.

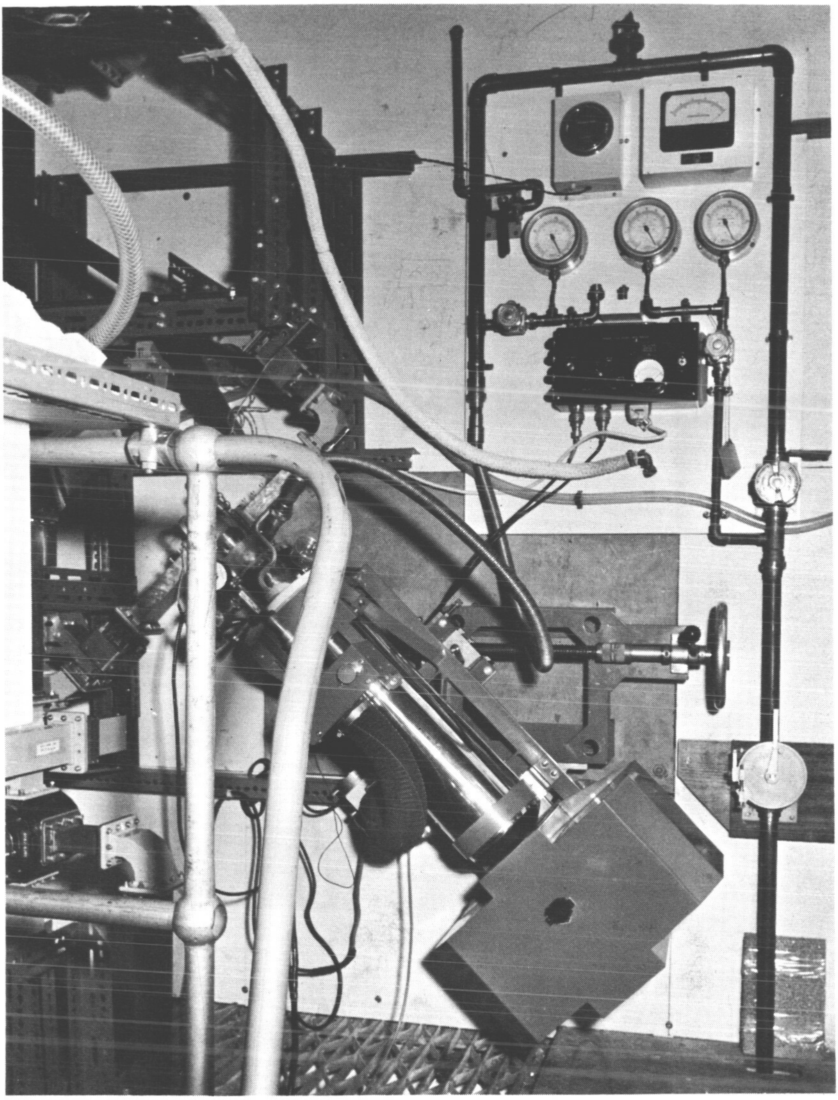

Fig. 9 — Maser installed at Goonhilly.

Fig. 10 — Maser with large dewar at Goonhilly.

ACKNOWLEDGMENT

The design, construction, and testing of this maser was completed in six months. This rapid development would not have been possible without the enthusiastic and able cooperation of Messrs. J. M. W. Cook, J. D. A. Day, E. L. Hentley, D. G. Stevenson, M. C. Kite and other of the authors' colleagues at Mullard Research Laboratories which they gratefully acknowledge. The authors would also like to acknowledge the generous assistance in respect of equipment and installation given by Dr. H. N. Daglish and Mr. M. R. Child of the GPO Research Establishment, Dollis Hill.

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