June 2, 1964 F. E. GOODWIN ETAL 3,135,925

COUPLED CAVITY NONRECIPROCAL TRAVELING WAVE MASER SYSTEM

Filed Oct. 10, 1961 2 Sheets-Sheet 1

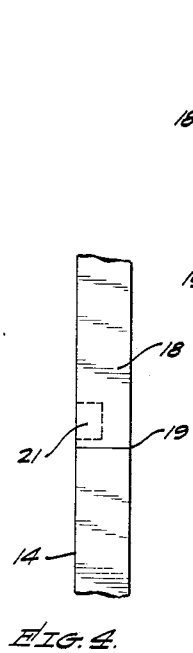


FIG. 4.

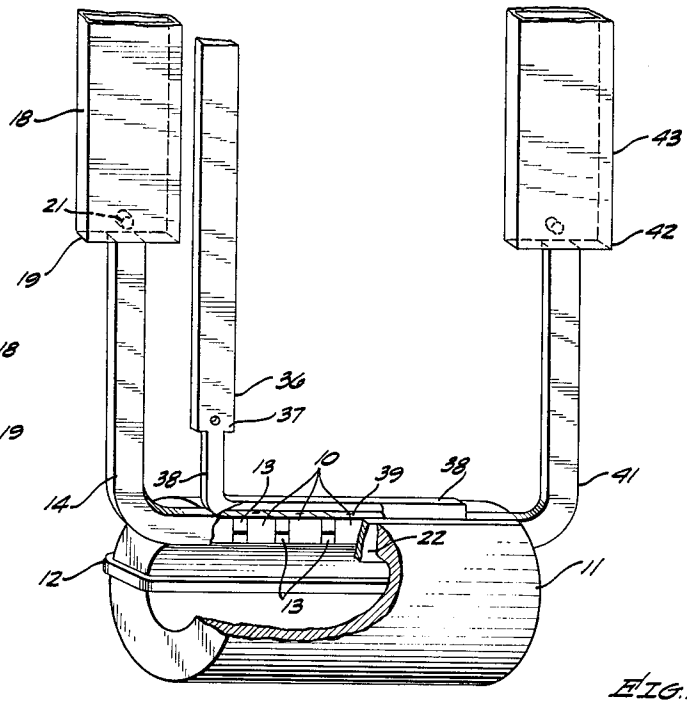


FIG. 1.

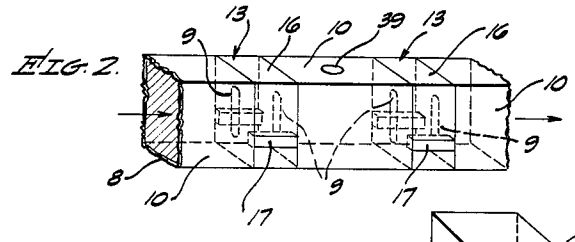


FIG. 2.

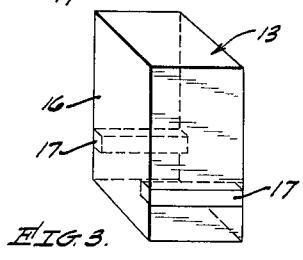


FIG. 3.

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COUPLED CAVITY NONRECIPROCAL TRAVELING WAVE MASER SYSTEM

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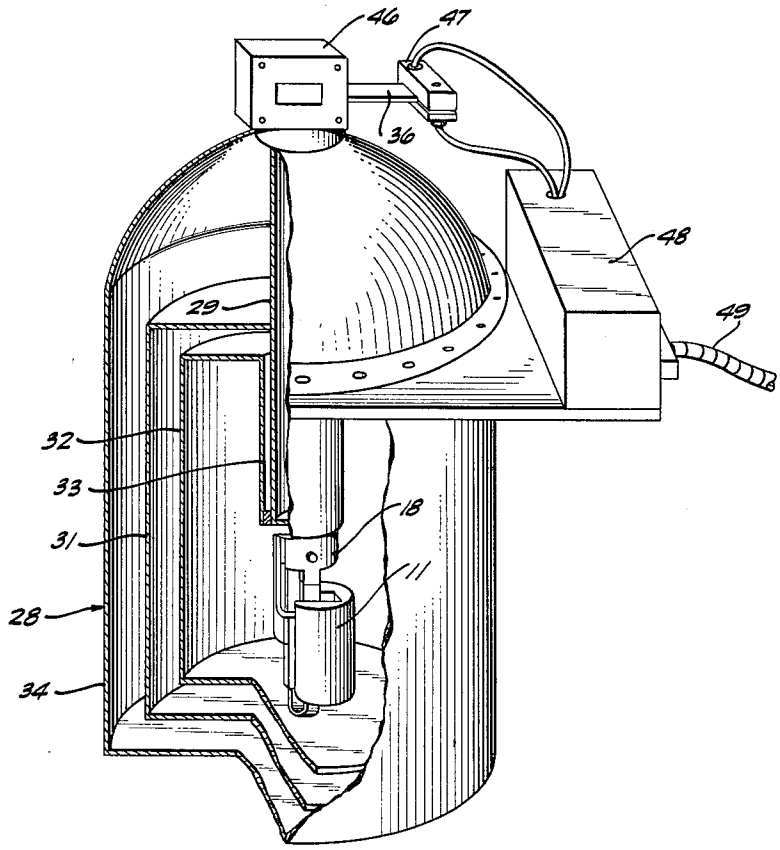


FIG. 5.

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COUPLED CAVITY NONRECIPROCAL TRAVELING WAVE MASER SYSTEM

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12 Claims. (Cl. 330—4)

This invention relates to a system for microwave amplification by stimulated emission of radiation, known as a maser system, and in particular to a traveling wave maser system adapted to provide low noise amplification in the microwave and millimeter wave regions of the spectrum.

Among the disadvantages of those prior art masers, which are considered to be of the traveling wave type, is that they are difficult to fabricate for operation at higher frequencies, such as above about 6000 mcs. Some of them require very high magnetic energies which in turn require large, heavy magnets. Such masers also occupy an excessive amount of space and are not adaptable for use in portable or mobile systems.

It is among the objects of this invention to provide a maser system capable of fulfilling communications and radar systems requirements where stability, reliability of performance, small physical size and serviceability are the most important criteria.

Additional objects of the invention will become apparent from the following description, which is given primarily for purposes of illustration, and not limitation.

Stated in general terms, the objects of the invention are attained by providing a traveling wave maser system which includes a series of coupled ruby cavities, each functioning as an amplifier, and separated by a resonance type ferrite isolator. The resulting device preferably is cooled to a very low temperature, such as that of liquid helium (4.2° K.), by the use of an appropriate Dewar or refrigerator system. Under active conditions, this resulting cascaded amplifier behaves as a lumped parameter filter with negative conductance, which supplies gain to the system. The value of the isolator is chosen so that stable net forward gain is achieved, but appreciable reverse gain through the structure is not encountered.

Input signals are brought into the system through a conventional waveguide, which is transformed into a solid waveguide by means of an RF transformer. The pump power is brought into the system in a similar manner. The transformer includes a section of dielectric loaded waveguide. By the use of a shaped stub arrangement in the transformer, an extremely broad band susceptance match is obtained. The resulting transformer gives a very good impedance match over a broad frequency range (20% bandwidth) and allows the signal and pump RF energy to be matched into the coupled ruby cavities. The pump power, which is at a frequency two or more times that of the signal frequency, provides the necessary excitation to the rubies. The RF signal is amplified in the coupled ruby cavity section and transmitted through another section of solid waveguide and impedance transformer to a waveguide which takes the signal out of the maser system.

A more detailed description of the invention is given below with reference to the appended drawings, wherein:

FIG. 1 is an isometric view schematically showing the traveling wave maser system of the invention;

FIG. 2 is a partial view, drawn to an enlarged scale, of the ruby cavities separated by isolators;

FIG. 3 is an enlarged isometric view showing details of an isolator unit;

FIG. 4 is an enlarged partial side view showing an RF transformer, including a shaped stub, between a conventional waveguide and a solid waveguide; and

FIG. 5 is an isometric view, with portions of a Dewar cut away, schematically showing an assembled traveling wave maser system.

Maser performance is improved considerably in a coupled cavity maser system over that of a single cavity system. In order to achieve optimum maser performance, it is necessary to set the coupling between two or more maser cavities to a precisely determined value. The coupling between the cavities serves two essential purposes. First, to adjust the loaded Q of each cavity and second, to provide the necessary coupling between the active cavities to form the filter circuit.

The high performance maser cavities employed in the maser of this invention are rectangular pieces or cavities **10** of active material, such as ruby, which is plated with silver, as indicated at **8** in FIG. 2. The ruby maser material preferably contains from about 0.06 to about 0.08 percent Cr_2O_3 upon analysis, which gives a spin-ion concentration of approximately $N_0=2.5\times10^{19}$ ions/cm.^{3}. The silver plating forms the cavity **10**. An iris **9** is formed by removing a portion of the plating from a side wall of each cavity **10** to form an opening through the plating. Two cavities can be coupled by forming irises in the plating on opposite sides of the pieces of plated ruby, and aligning the pieces so that their irises also are aligned. The coupling of two cavities in this manner is determined by the susceptance of the resulting coupled irises of the two adjacent cavities. However, the susceptance of the coupled irises is proportional to the sixth power of the diameter of the coupled irises.

It is extremely difficult to form an iris **9** with the precise size to achieve the desired cavity coupling. Furthermore, in the case of masers, the cooled cavity employing ruby as the active material at 4.2° K. is somewhat different in properties than it is at ordinary temperatures, such as room temperatures. Cavity coupling adjustments made at room temperatures usually are incorrect at liquid helium temperatures.

A highly accurate method of setting the susceptance of an iris has been derived. This is done at room temperatures, thereby eliminating the need of costly experimentation at low temperatures. The method consists of observing the frequency of cavity absorption when the iris is shorted, and when the iris is open circuited. The shift in the resonant frequency determines the susceptance, as calculated from impedance formulas.

In practicing this method, a silver plated ruby cavity **10** is inserted in a jig and an iris **9** of a particular size is cut by removing part of the silver from the end wall of a cavity. The susceptance is then measured electrically. If it is found to be different from the desired value, the procedure is repeated. When the precise iris size has been achieved, a mask is made so that the iris can be reproduced exactly on as many rubies as desired. Thus, among the advantages of this invention over usual methods are that the loaded Q of the cavities **10** can be precisely adjusted to prevent oscillation and give optimum performance, and the coupling between cavities can be adjusted so that particular amplifying characteristics are achieved.

The resulting cavity arrangement constitutes a slow-wave structure of a particular type, i.e., one in which the magnetic energy required for maser action and isolation is hundreds of times less than that of prior art traveling wave masers. Thus, the magnetic energy can be provided by a self-contained permanent magnet **11** with trimming coils, such as coil **12**. The magnetic field can be permanently set by pulsing the trimming coil **12**, thereby providing a permanent and stable magnetic field, eliminat-

ing the need for inefficient highly regulated power supplies.

The microwave isolators **13** serve a very important function in the traveling wave maser of this invention. The source of oscillation is the microwave energy traveling through the maser in the reverse direction. This is usually caused by reflections at the output of the amplifier. It is necessary to eliminate this energy, traveling in the reverse direction, which shall be referred to as the reverse wave, while at the same time leaving the forward wave unaffected. This is done within the maser structure itself and the environmental conditions of the maser are thus forced upon the isolators **13**. They operate at 4.2° K., and their physical size is reduced because of dielectric loading so that they fit between the ruby cavities **10** of the maser in their waveguide **14**. In actual practice, a D.C. magnetic field is maintained normal to waveguide **14**, the strength of which is fixed by the particular maser. The dielectric constant of the isolator used in a specific embodiment of this invention is the same as that of ruby, which is 10.

Presently there are no other isolators which perform the operation and accomplish the objectives of this invention. In general, conventional isolators are very large, are built around a standard air-filled waveguide, and are designed to operate at room temperature, rather than at 4.2° K. The disadvantages of isolators in full-sized, unloaded waveguide are obvious. It would be impossible to use them for the purposes given above because of the size and weight factors involved in their use.

The isolators **13** of this invention are made of vitrified alumina **16** and yttrium iron garnet **17**. The alumina **16** is used primarily as a holder for the small pieces **17** of garnet which produce the non-reciprocal action. The holders **16** are machined to the proper dimensions out of the vitrified alumina, and the pieces **17** of garnet are similarly machined. The pieces **17** of garnet are then snugly fitted into slots cut in the alumina pieces **16**, as best shown in FIG. 3. The side walls of the isolators may be plated with silver, the end walls being unplated.

The principle of operation of isolators **13** is as follows. A D.C. field is applied to the isolator **13**. If a circularly polarized RF magnetic field is in the vicinity of the garnet **17**, the isolator **13** absorbs energy. If the applied RF field is circularly polarized in the opposite sense, no energy is absorbed. Thus, microwave energy will pass unattenuated in one direction but not in the opposite direction. The pieces of garnet **17** are placed in a plane where the magnetic fields in the normal mode of the guide are such that circular polarization results. The pieces of garnet **17** are shaped so that the ferromagnetic resonance absorption described above occurs at the required field for the maser.

The isolators **13** of this invention possess several advantages. First, they can operate at 4.2° K. and can thus be put inside the maser Dewar. Also, due to complete dielectric filling, they are very small and can be placed between the ruby cavities **10** of the maser in the same waveguide **14**, without the need for transitions, thereby reducing the required magnetic energy to a minimum. For the same reason, the isolators **13** cause less reflection since they are made of materials all of which have substantially the same dielectric constant (about 10), as compared to the use of air and ferrites. In addition, the isolators **13** utilize the same magnetic field used for the ruby cavities **10** of the maser and do not require an individual magnet. Furthermore, the isolators **13** easily can be lengthened in order to obtain any desired amount of isolation.

Another advantage resulting from separating resonator elements by an isolator element (rather than including the isolator in the resonator, as in prior art devices), is that greater gain to loss ratios are inherently possible, allowing the maser of the invention to function as an amplifier at 4.2° K., rather than at 1.8° K., as for prior art devices.

In order to produce stable microwave circuitry at liquid helium temperatures, a miniature solid waveguide **14** was developed using alumina as the dielectric loading material. Dielectric loading permits a reduction in the linear dimensions of the waveguide **14** by a factor of more than three, as compared with an air-filled waveguide **18**. Waveguide **14** was fabricated by machining the required configuration from alumina and then electroplating a layer of copper onto the surface to provide a conductive waveguide wall, as well as to give additional strength. This construction not only results in a reduction in size of the system, but also has solved the problem of lossy frozen air and water within the waveguide while it is immersed in a liquid helium bath. In addition, since alumina has essentially the same dielectric constant as ruby, it matches directly into the ruby elements of the maser. The waveguide loss is ¼ db/inch at liquid helium temperatures and 1 db/inch at room temperatures.

In order to effect a broadband low loss, low reflection coupling of microwave energy from the air filled waveguide **18** to the smaller alumina filled waveguide **14**, a transition section **19** was used. In an analysis of the admittance of the waveguides **18** and **14** it was found that in order to equate the admittances for a broad range of frequencies, it is necessary that the E dimension of both waveguides be the same, and that the H dimension be in the relationship of the inverse square root of the dielectric constants of the materials in the respective waveguides **18** and **14**.

Well known means may be used to adjust the waveguide sizes to meet the above conditions. Once the above conditions are met, the two waveguides may be abruptly brought together at a plane where the only mismatch is a pure susceptance. By placing an experimentally determined post **21** very close to the susceptance plane, a broadband cancellation of said susceptance may be achieved.

The permanent magnet **11** preferably is made of Alnico V and the pole pieces **22** thereof preferably are made of 1020 HR steel. A tuning coil **12** is placed on one, or both, of the pole pieces **22** to provide a trimming adjustment for the magnet. Tuning coil **12** is shown removed some distance from a pole piece **22** for clarity, but preferably is positioned closely adjacent a pole piece for better results. A simple capacitor discharge circuit (not shown) can be used to pulse the magnetic field strength of the magnet **11**, up or down, to achieve a permanent trimming adjustment. After this has been done, the magnet control circuit can be disconnected from the capacitor discharge circuit. A perfectly steady magnetic field is thus produced for the maser, eliminating the highly regulated power supplies required in prior art traveling wave masers. The use of a small permanent magnet **11** is made possible by a slow-wave structure (coupled cavities **10** and isolators **13**) which requires hundreds of times less magnetic energy than do prior art traveling wave masers.

A special air-filled waveguide **18** was prepared by fabricating a fine-grained fiberglass waveguide lined with 0.1 mil of gold, thus meeting the requirements of an access guide with the combined properties of low microwave loss, extremely low thermal conductivity, stability under severe thermal shock, and reasonable mechanical strength. The development of this special waveguide **18** has allowed the entrant waveguides to the maser to be reduced in overall length by a factor of four. In view of the fact that the size of prior art maser Dewars is determined by the length of the entrant waveguides, this development has permitted a reduction in Dewar size by a considerable amount.

Since it is required that the amplifier unit be maintained at the temperature of liquid helium (4.2° K. at atmospheric pressure), a Dewar is necessary. Conventional open-neck Dewars have limitations regarding the angle of operation because the fluid spills out. A Dewar **28** of a special re-entrant design, shown in FIG. 5 allows the de-

vice to be inverted without loss of the cryogenic fluid. The short length neck **29** of Dewar **28** is made possible by special fiberglass waveguide **18** which provides minimum RF loss and maximum thermal insulation.

Both the maser Dewar **28** and an intermediate storage Dewar (not shown) are of all-metal construction. They utilize an advanced design in which the usual liquid-nitrogen-filled jacket is replaced by a radiation shield **31** cooled approximately to the temperature of liquid nitrogen by the helium gas as it escapes from the Dewar.

After the helium gas boils off in the inner helium reservoir **32**, it is passed through a heat exchanger consisting of neck **29** and re-entrant portion **33**, which is built into the filling neck of the Dewar. Almost all of the heat flowing into Dewar **28** is absorbed by the helium gas as it warms up from 4.2° K. to the ambient temperature. The largest heat input is by conduction through the stainless steel neck **29**, which should have strength sufficient to support the helium reservoir **32** and the radiation shield **31**. A smaller amount of heat enters by way of the RF transmission lines and by radiation to the shield **31**. The heat exchanger arrangement **29, 33** is designed to intercept as much of this heat as possible before it reaches the liquid helium. The necessity for minimizing the heat that reaches the helium and the efficiency of the gas as a coolant are illustrated by the fact that a heat input of 150 mw. into the liquid helium will boil off about ⅕ liter/hour. The gas thus created is capable of absorbing about 10 watt-hours of heat in heating from 4.2° to 290° K.

The re-entrant portion **33** of the helium container **32** makes it possible to operate Dewar **28** in any position. This is a definite advance over prior-art Dewars. The maser circuit is built integrally with the heat exchanger, as shown in FIG. 5. This complete unit is inserted through the neck **29** of the Dewar **28**. The inside of the helium reservoir **32** is plated with conducting metals (copper and gold) in order to ensure a uniform temperature of 4.2° K. regardless of the amount and location of liquid helium present. Provision is made for thermal contact between the waveguide **14** which contains the maser material and the re-entrant wall **33** of the reservoir. Thus good thermal contact is maintained between the active maser circuit and the liquid helium. The radiation shield **31** contains several holes (not shown), which permit the unit to be evacuated by a valved vacuum connection (not shown) on the outer container wall **34**.

In the embodiment of the invention shown in FIG. 5, unit **46** contains the input-output waveguides **18** and **43** respectively, **36** is the pump waveguide, **47** is a K-band pump klystron, **48** houses the magnet charging circuit, and **49** is the klystron power and magnet control cable.

The maser Dewar unit and the magnet charging unit **48** are located as close as possible to the source of the signal, such as at the focal point of a parabolic antenna (not shown). This is made physically feasible by the lightness of the units, which together weigh 25 lbs. The maser Dewar **28** is filled with liquid helium. When the maser reaches its operating temperature, appropriate sensing elements cause an indication on a control panel (not shown). The control panel may be located thousands of feet from the maser, such as in an operating room.

When the pump power supply is turned on, pump power is supplied to the rubies **10** by way of the pump waveguide circuit consisting of a conventional waveguide **36**, an RF transformer or transition section **37** and a solid waveguide **38**. The pump energy is slot-coupled into each ruby **10** from waveguide **38** through pump slots **39**. The rubies **10** are thus activated. Signals entering the signal waveguide **18** are transformed to solid waveguide **14** by means of impedance transformer or transition **19**.

Since the rubies **10** are active, the coupled rubies behave as a lumped parameter filter with negative conductance, which has the effect of amplifying the signals which come into the input **18** of the filter circuit. The signals grow in amplitude as they pass through the filter, such that the power level of the signal is 100 to 1000 times greater at the output **41** than at the input **14**. The isolators **17** prevent net gain in the reverse direction through the filter, adding stability to the device. The amplified signal is taken out through solid waveguide **41**, another impedance transformer or transition **42**, and transmitted through conventional waveguide **43** to a following receiver stage, such as a mixer or traveling wave tube amplifier (not shown).

By virtue of the high gain of the maser, the effects of the noise in the following stages of the receiver are reduced to a negligible value. The low noise characteristics of the maser provide an over-all receiver noise temperature of considerably less than 25° K., compared to about 2500° K. for conventional receivers. The added sensitivity of the receiver brought about by the reduction of receiver noise permits detection of very weak signals from sources such as space probes or satellites which otherwise would go undetected.

Obviously many other modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention can be practiced otherwise than as specifically described.

What is claimed is:

1. A traveling wave maser system comprising a series of solid, aligned maser material resonators electrically coupled with respect to each other, a resonance type ferrite isolator positioned in alignment between each pair of adjacent maser material resonators in the series thereof for achieving forward gain through the series and preventing backward gain therethrough, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

2. A traveling wave maser system comprising a series of aligned ruby maser cavities spaced from each other by garnet isolators, said ruby cavities being plated with a metal and coupled through irises formed through the plating, said garnet isolators being mounted in vitrified alumina holders for achieving forward gain through the ruby cavities and preventing backward gain therethrough, means for maintaining a magnetic field transversely of the aligned ruby cavities, signal input and signal output means coupled with the coupled ruby cavities for amplification of input signals, and pump means cooperatively associated with the ruby cavities for exciting the maser material therein.

3. A traveling wave maser system according to claim 2, wherein said signal input and said signal output means each comprise a waveguide transition section, said transition section including an abrupt change of dielectric constant in a transition plane in the section, means for adjusting the admittance to substantial equality in the transition plane, said admittance equality being substantially equal over a wide frequency range, and means for broadband matching the susceptance remaining at the transition plane.

4. A traveling wave maser system according to claim 2, wherein the means for maintaining a magnetic field is a permanent magnet mounted around the ruby cavities and provided with a trimming coil adjacent a pole of the magnet.

5. A traveling wave maser system according to claim 2, wherein the signal input and signal output means are dielectric loaded solid waveguides, each connected to air-filled waveguides through a transition section including a metal stub element for impedance matching.

6. A traveling wave maser system according to claim 2, wherein the pump means includes a dielectric-loaded

solid wave-guide coupled to the ruby cavities through slot means formed through the metal plating of the cavities.

7. A traveling wave maser system according to claim 2, wherein the ruby cavities, garnet isolators and magnetic field means are maintained at liquefied gas temperatures by submergence in a body of liquefied gas, and a Dewar containing a reservoir for the liquefied gas, the Dewar being provided with a re-entrant portion for connection thereto of the maser and to prevent spillage of liquid from the Dewar while inverted.

8. A traveling wave maser system comprising a series of solid, aligned maser material resonators electrically coupled with respect to each other, the coupling between the resonators being set at predetermined values calculated to adjust the loaded Q of each resonator to form a filter circuit, a resonance type ferrite isolator positioned in alignment between each pair of adjacent maser material resonators in the series thereof for achieving forward gain through the series and preventing backward gain therethrough, the dielectric constant of the isolators being substantially equal to that of the resonators, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

9. A traveling wave maser system comprising waveguide means, a series of aligned ruby maser material resonators electrically coupled with respect to each other, said ruby resonators containing from about 0.06 to about 0.08 percent Cr_2O_3 upon analysis, a resonance type ferrite isolator positioned in alignment between each pair of adjacent maser material resonators in the series thereof for achieving forward gain through the series and preventing backward gain therethrough, said resonators and said isolators being aligned in said waveguide means and dimensioned to fill the waveguide means dielectrically, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

10. A traveling wave maser system comprising a series of solid, aligned maser material cavities spaced from each other by resonance type ferrite isolators positioned in alignment between each pair of adjacent maser material cavities, said maser material cavities being plated with a metal and electrically coupled through irises formed through the plating, the coupling between the cavities being set at predetermined values calculated to adjust the loaded Q of each cavity to form a lumped parameter filter with negative conductance for achieving forward gain through the series of cavities and preventing backward gain therethrough, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

11. A traveling wave maser system comprising a series of aligned ruby maser cavities spaced from each other by garnet isolators positioned in alignment between each pair of adjacent ruby maser material cavities, said ruby maser material cavities being plated with a metal and electrically coupled through irises formed through the plating, the coupling between the cavities being set at predetermined values calculated to adjust the loaded Q of each cavity to form a lumped parameter filter with negative conductance for achieving forward gain through the series of cavities and preventing backward gain therethrough, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

12. A traveling wave maser system comprising waveguide means, a series of aligned ruby maser cavities spaced from each other by yttrium iron garnet isolators positioned in alignment between each pair of adjacent ruby maser material cavities, said ruby maser material cavities being plated with a metal and electrically coupled through irises formed through the plating, the coupling between the cavities being set at predetermined values calculated to adjust the loaded Q of each cavity to form a lumped parameter filter with negative conductance for achieving forward gain through the series and preventing backward gain therethrough, the dielectric constant of the cavities being substantially equal to that of the isolators, said cavities and said isolators being aligned in said waveguide means and dimensioned to fill the waveguide means dielectrically, means for maintaining a magnetic field transversely of the series of maser material resonators, signal input and signal output means coupled with the series of maser material resonators for amplification of input signals, and pump means cooperatively associated with the series of maser material resonators for exciting the maser material therein.

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