Extension of the Laser-Pumped Ruby Maser to Millimeter Wavelengths*

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Summary—A brief description is given on the operation of a microwave ruby maser in which the pump signal is the optical emission of a ruby laser. For operation in the millimeter spectrum the application of a magnetic field of inordinately high intensity can produce Zeeman splitting of the Cr^{3+} levels at millimeter wave energy in the ground state in ruby. To obtain population inversion by optical pumping on the levels requires that the ratio of maser frequency to temperature be $\nu_{ij}/T<14.4$ Gc/sec °K. As the maser temperature is increased the spin lattice relaxation time T_1 decreases in addition to possibly decreasing with increasing magnetic field. Since the power required from the laser is estimated as that required to produce saturation of the optical pump transition in a time less than T_1, then decreasing T_1 also requires increased laser emission. A broadening of the laser emission has been observed at increased power so that the limit on useful laser power can be given in terms of the absorption line width of the maser optical pumping transition. Treating these various effects conservatively indicates that the laser-pumped ruby maser can be operated over the entire millimeter spectrum, however. The design of an apparatus with a hard superconductor electromagnet producing the field intensity required to accomplish this objective is given.

Introduction

MASER OPERATION in the millimeter spectrum at frequencies higher than about 100 Gc/sec has been largely limited by the availability of suitable pump signal generators, although maser gain at frequencies exceeding the pump frequency has been demonstrated. At the highest frequency of 96 Gc/sec reported[1] the maser operated at somewhat below the second harmonic of the pump frequency. In addition, Wagner, *et al.*,[2] and Morris[3] have reported gain at the second harmonic of an X-band pumped staircase maser, and multiple photon effects which give gain at higher harmonics are discussed at this conference. With the advent of lasers, the frequency and power limitations of conventional tubes used as the maser pump-signal generators have been circumvented. However, the longest laser emission wavelength of 18.5 μ reported to date[4] is still well outside the millimeter spectrum.

The concept of the application of the laser output as a pump signal to obtain additional laser and maser effects opens up a number of possibilities. For example, multiple photon processes were recently observed in which the ruby laser output was used as the pump signal in Raman active liquids to obtain optical lasers at wavelengths longer than the pump wavelength.[5] The utilization of the laser signal in a laser-pumped ruby maser at microwave frequencies was also accomplished in an experiment[6] more directly related to the original concept of the solid-state maser of Bloembergen.[7] We wish to briefly discuss the technique employed in the laser-pumped ruby maser and to consider the possibilities of extending the maser wavelength well into the millimeter spectrum.

Laser-Pumped Ruby Maser at 22.4 Gc

The energy levels of Cr^{3+} in ruby pertinent to the laser-pumped maser are shown in Fig. 1. The objective in optically pumping ruby was to deplete the population of an intermediate Zeeman level of the $^4A_2$ ground state of Cr^{3+} by saturating a Zeeman component of the optical R_1 transition in absorption. Population inversion and maser gain would then follow if the unperturbed populations of higher levels in the ground state sufficiently exceeded the remaining population of that depleted level. At liquid helium temperature the radiative lifetime of the R_1 transition is 8 msec and the spin-lattice relaxation time T_1 is considerably longer at about 100 msec. The output of the laser persists for about 1 msec so that we may therefore neglect relaxation and consider the pump signal to be delivered instantaneously in this case. In other words, we estimate that our maser pump power requirement is determined by the number of R_1 photons necessary to produce saturation of the pump transition in a time less than the spin-lattice relaxation time of the maser transition.

The R_1 energy and linewidth in fluorescence vary with temperature, as shown in Fig. 2. In addition, the spectral character of the stimulated emission of the ruby laser has been observed to be temperature dependent

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[1] W. E. Hughes, "Millimeter-wave maser," *Bull. Am. Phys. Soc.*, vol. 7, p. 445; August, 1962.

[2] P. E. Wagner, J. G. Castle, and P. F. Chester, "Inversion by fast passage in a multilevel spin system," *J. Appl. Phys.*, vol. 31, p. 1498; August, 1960.

[3] R. J. Morris, "The Staircase Maser," Stanford Electronics Labs., Stanford Univ., Stanford, Calif., Tech. Rept. No. 211-3; January 22, 1962 (unpublished)

[4] C. Patel, "Present Status of Gaseous Optical Masers," presented at the Ohio State Univ. Symp. on Lasers and Applications, Columbus, Ohio; November, 1962.

[5] G. Eckhardt, R. W. Hellwarth, F. J. McClung, S. E. Schwarz, D. Weiner, and E. J. Woodbury, "Stimulated Raman scattering from organic liquids," *Phys. Rev. Letts.*, vol. 9, pp. 455–457; December 1962. Also, presented at Optical Society of America Meeting, Rochester, N. Y.; October, 1962.

[6] D. P. Devor, I. J. D'Haenens, and C. K. Asawa, "Microwave generation in ruby due to population inversion produced by optical absorption," *Phys. Rev. Lett.*, vol. 8, pp. 432–436; June 1, 1962.

[7] N. Bloembergen, "Proposal for a new type solid state maser," *Phys. Rev.*, vol. 104, pp. 324–327; October 15, 1962.

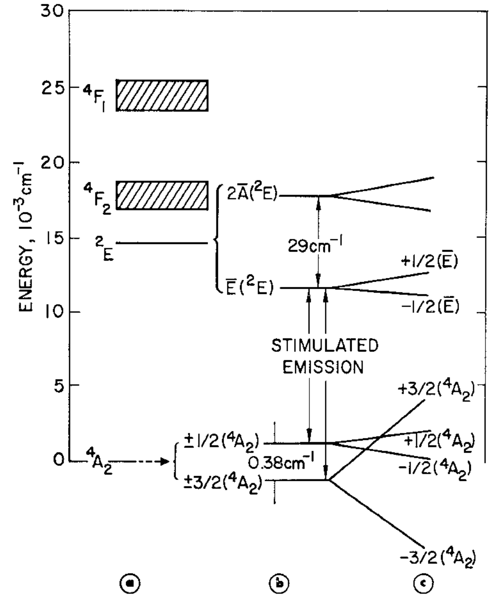

Fig. 1—Energy level diagram of Cr^{3+} in ruby. (a) $^4F_1$ and $^4F_2$ are the laser-pumping absorption bands. (b) Expanded scale shows splitting of $^4A_2$ and ^2E in zero magnetic field and laser emission transition. (c) Zeeman levels.

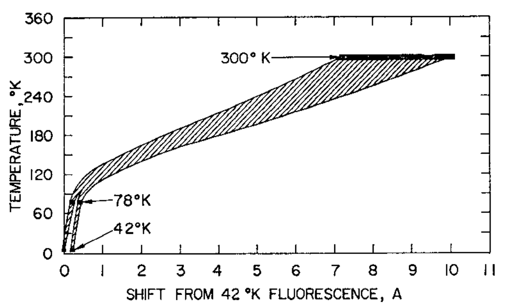

Fig. 2—Spectral shift and width of R_1 fluorescence vs temperature. The darkened areas correspond to the fluorescent spectra. (From I. J. D'Haenens and C. K. Asawa[8].)

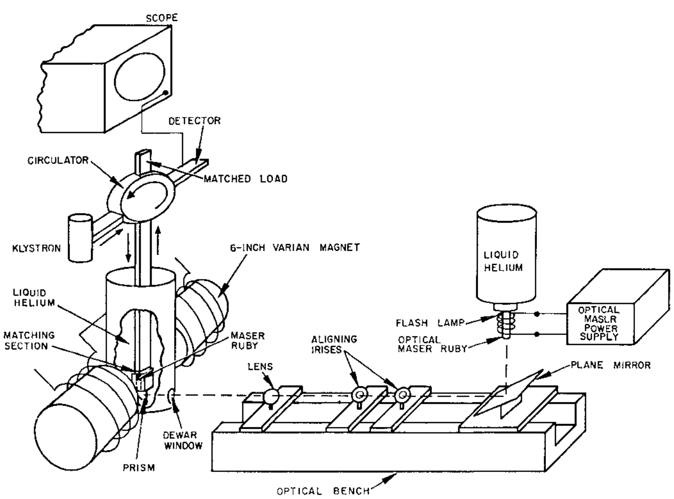

Fig. 3—Arrangement of experimental apparatus.

also.[8–10] In the laser-pumped maser experiment the laser ruby was cooled by conduction to liquid helium, and a shift of 0.22 cm^{-1} towards longer wavelengths from the fluorescence wavelength was observed at laser threshold. As the laser oscillation was driven above threshold, the emission was observed to cover a broader band than at threshold possibly sweeping in time during the laser-pumping lamp pulse. For the present purpose of description of the laser-pumped maser, we may regard these effects as empirical details, although not necessarily negligible since the broadening limits the amount of pump power which can be spectrally matched to the maser pump transition.

Since the maser pump signal was fixed by the spectral characteristics of the laser emission, then we appropriately oriented the maser crystal in a magnetic field such that a component of the Zeeman structure of the R_1 line was used as the pump transition. This, in turn, determined the maser frequency and, because of the complex level structure in ruby, resulted in about ten possibilities ranging up to 58 Gc in magnetic fields up to 20 koe, under the conditions described above. To obtain a large filling factor in the microwave resonator and also to achieve a minimal volume of the resonator and thus minimize the pump power, we chose to operate at 22.4 Gc. The arrangement of the experimental apparatus is shown in Fig. 3. The K-band resonator consisted of a one-half inch length of 0.050- ×0.130-inch waveguide which was beyond cutoff at 22.4 Gc, but propagating in a section loaded with 0.078-inch length of ruby. The open end of the guide provided the optical path.

Extension of the Maser Frequency in Ruby

Increased splitting of the ground state (and excited state) levels in ruby can be obtained with larger magnetic fields, and maser operation at 58 Gc can probably be achieved with the same apparatus and a field of 20 koe by modifying the microwave resonator to that frequency. To consider the conditions for obtaining population inversion let the equilibrium populations of a pair of nondegenerate levels be n_i and n_j. Then n_i is related to n_j by the Boltzmann factor such that

$$\frac{n_j}{n_i} = e^{-h\nu_{ij}/kT},$$

where level j is of energy $h\nu_{ij}$ above i and $k/h = 20.8$ Gc/sec °K. Saturation of the pump transition $i \rightarrow m$,

[8] I. J. D'Haenens and C. K. Asawa, "Stimulated and fluorescent optical emission in ruby from 4.2°K to 300°K; zero field splitting and mode structure," *J. Appl. Phys.*, vol. 33, pp. 3201–3208; November, 1962. The data of Fig. 2 includes the results of K. S. Gibson, "The effect of temperature upon the absorption spectrum of a synthetic ruby," *Phys. Rev.*, vol. 8, pp. 38–43; July, 1916. Also the data of Schawlow and Devlin given by P. P. Kisliuk and W. S. Boyle, "The pulsed ruby maser as a light amplifier," Proc. IRE, vol. 49, pp. 1635–1639; November, 1961.

[9] I. D. Abella and H. Z. Cummins, "Thermal tuning of ruby optical maser," *J. Appl. Phys.*, vol. 32, pp. 1177–1178; June, 1961.

[10] T. P. Hughes, "Time-resolved interferometry of ruby laser emission," *Nature*, vol. 195, pp. 325–328; July 28, 1962.

in which i is the lower level, will deplete half of n_i since m is a level of the $\bar{E}$ excited state in ruby and is virtually unpopulated even at room temperature. Population inversion then requires that at thermal equilibrium $2n_j > n_i$, or

$$\nu_{ij}/T < 14.4 \text{ Gc/sec } ^\circ\text{K}.$$

Thus, at 4.2°K the limiting maser frequency is about 60 Gc/sec, neglecting losses and also the relaxation transitions $\bar{E} \rightarrow {}^4A_2$.

Thus, to obtain a laser-pumped ruby maser out of the end of the millimeter band at 300 Gc/sec, the maser will have to operate at a temperature above 20.8°K, which is slightly higher than the boiling point of liquid hydrogen and somewhat lower than that of liquid neon. The spin-lattice relaxation time and radiative lifetime still exceed the laser emission time at 20.8°K,[11] at K band, although there exists some reason to expect that T_1 may decrease with increasing magnetic field. The work of Nash and Rosenwasser[12] with copper tutton salt and Scott and Jeffries[13] with salts of Nd indicated such an effect, but Pace *et al.*,[14] report that T_1 appears to remain constant with increasing frequency for 0.1 per cent ruby, at least over the frequency range 7.2 to 34.6 Gc/sec. Also, the pulsed-field experiments of Momo, *et al.*,[15] indicate at least only a small T_1 magnetic field dependence in ruby.

Assuming that we have a suitable maser resonator and cryogenic system, and that we are not limited by the magnetic field intensity, then the remaining problem in extending the maser frequency is to match the maser pumping transition to the laser emission. In a large magnetic field H the Zeeman levels of the ${}^4A_2$ ground state are essentially linear with H and independent of orientation of the ruby c axis with respect to H. Since the Zeeman levels of the excited $\bar{E}$ state vary with orientation then the analysis of the problem is somewhat simplified. A plot of the energy of the possible pumping transitions in high field is shown in Fig. 4. The origin of the ordinate axis is chosen as the mean energy of the zero field transitions $\pm\frac{3}{2}({}^4A_2) \leftrightarrow \bar{E}$ and $\pm\frac{1}{2}({}^4A_2) \leftrightarrow \bar{E}$, which varies as the temperature of the maser ruby, as

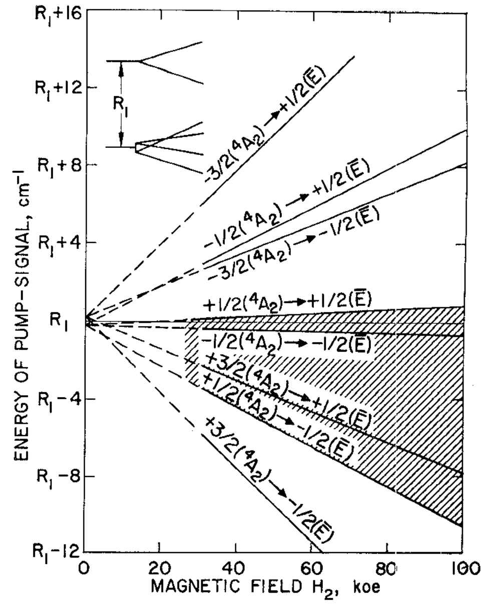

Fig. 4—Tuning range of a maser pump transition in high magnetic field. Energies of the ${}^4A_2 \rightarrow \bar{E}$ Zeeman transitions with H parallel to the c axis are shown. In high field ($H \gtrsim 30$ koe) the ${}^4A_2$ levels do not vary with orientation θ, but $\bar{E}$ levels do. Consequently, the energies of the $+1/2({}^4A_2) \rightarrow \pm 1/2(\bar{E})$ transitions will fall within the shaded area as θ varies from 0 to $\pi/2$.

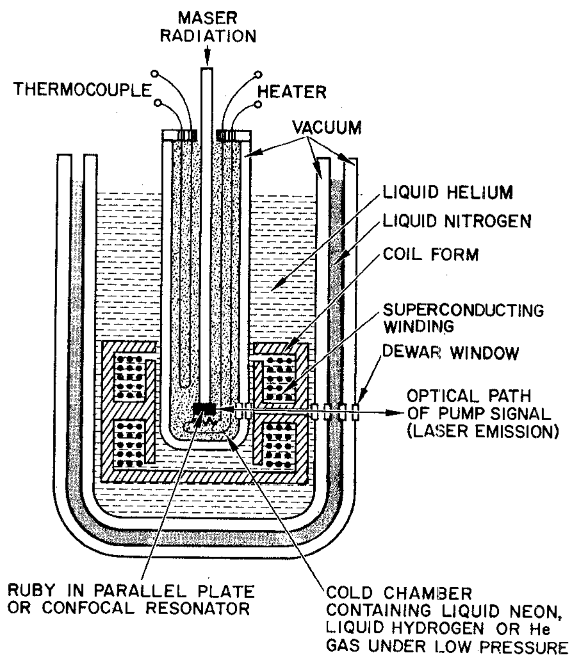

Fig. 5—Cross section of superconducting magnet and cryogenic system of maser for laser-pumped ruby maser.

shown in Fig. 2. Thus, to deplete the $+\frac{1}{2}({}^4A_2)$ level, for example, Fig. 4 shows that the laser emission need only have a component somewhere between $(R_1+0.9)$ cm^{-1} and $(R_1-10.5)$ cm^{-1} in a field 100 koe. The maser transition would then be the $+\frac{3}{2}({}^4A_2) \rightarrow +\frac{1}{2}({}^4A_2)$ at a frequency of 267 Gc/sec, which is an allowed ground state transition. In this case, the laser could be operated at liquid nitrogen temperature insofar as the problem of

[11] *Note added in proof:* A laser-pumped ruby maser at 77°K at which temperature $T_1 \simeq 50$ μsec has been operated by G. M. Zverev, A. M. Prohhorov, and A. K. Shevchenko, "Generation of the millimeter waves in optically pumped ruby," submitted to *J. Exptl. Theoret. Phys.* (U.S.S.R.), and reported at the Third Internatl. Symp. on Quantum Electronics, Paris, France; February, 1963. The cooled laser ruby was surrounded and in direct contact with liquid nitrogen which presumably results in improved spectral stability in the laser emission.

[12] F. R. Nash and E. Rosenwasser, "Cross relaxation and maser action in $Cu(NH_4)_2(SO_4)_2 \cdot 6H_2O$," "Quantum Electronics," Columbia University Press, New York, N. Y., pp. 302–305; 1960.

[13] P. L. Scott and C. D. Jeffries, "Spin-lattice relaxation in some rare-earth salts at helium temperature; observation of the phonon bottleneck," *Phys. Rev.*, vol. 127, pp. 32–51; July 1, 1962.

[14] J. H. Pace, D. F. Sampson, and J. S. Thorp, "Spin-lattice relaxation times in ruby at 34.6 Gc/sec," *Proc. Phys. Soc.*, vol. 76, pp. 697–704; November, 1960.

[15] L. R. Momo, R. A. Myers, and S. Foner, "Pulsed field millimeter wave maser," *J. Appl. Phys.*, vol. 31, p. 443; February, 1960.

obtaining a spectral match of the laser emission to the maser pump transition is concerned. On the other hand, the liquid nitrogen cooled laser emission is broader than the liquid helium cooled laser when driven above threshold. Consequently, a somewhat more severe limitation arises as to the amount of maser pump power which can actually be coupled into the maser ruby if a nitrogen cooled laser is employed.

The magnetic fields required in this scheme are feasible with superconducting solenoids which have critical temperatures below the higher frequency maser operating temperature, however. Consequently, we envisage the maser cryogenic system to consist of a triple dewar, *i.e.*, an outer nitrogen jacket, a second helium jacket for the superconducting magnet, and an inner cold chamber containing the maser ruby and a heater to control the temperature of the maser. A schematic depicting such apparatus is shown in Fig. 5.

Conclusion

A number of assumptions are required in outlining a procedure for operating the laser-pumped ruby maser at the highest possible frequency. Little directly related experimental data can be used to support these assumptions, and we may therefore only judge that the laser-pumped ruby maser appears feasible at a frequency in the neighborhood of 300 Gc/sec. Finally, we have confined our discussion to ruby, since we wished to be as concrete as possible in speculation. The study of other, either extant or forthcoming, three-level laser materials may well allow better methods of obtaining a laser-pumped maser than considered here.

The Re-Entrant Cross Section and Wide-Band 3-db Hybrid Couplers*

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Summary—**A new type of parallel-coupled TEM-mode cross section is described and named the re-entrant cross section. An analysis of the even- and odd-mode characteristic impedances of the re-entrant cross section shows it to have advantages in the case of tight coupling when compared to previously used parallel-strip cross sections. Close tolerances are easily held, and considerable misalignment is permissible. Two single-section 3-db couplers were tested with coupling curves very close to theoretical, and with good directivity. Then a three-section coupler having a re-entrant center section was designed for the 400- to 2000-Mc band, yielding a coupling variation less than 0.4 db and a minimum directivity of 29 db. Next a three-section coupler was designed for the 1- to 5-Gc band. A series of modifications resulted in a final model having a coupling variation within 0.5 db, and a minimum directivity of about 22 db.**

Introduction

BACKWARD-COUPLING parallel strip line couplers can theoretically be made to have nearly constant coupling over very large bandwidths by properly connecting coupled quarter-wave sections in cascade.[1-3] For example, one section yields 2:1 bandwidth with -3 ± 0.3-db coupling, while three sections in a symmetrical configuration can be designed to yield 3:1 bandwidth with -3 ± 0.1-db coupling, or 5.1:1 bandwidth with -3 ± 0.4-db coupling.[2] However, when using more than one section, discontinuity effects have previously reduced the coupler's directivity and increased its VSWR. Furthermore, it has been difficult to maintain sufficiently tight dimensional tolerances in the very closely spaced strips of the center section. Because of these problems, prior work on three section 3-db couplers for 3:1 bands has resulted in low directivity.[2] The situation is even more severe for designs of greater bandwidth.

In order to alleviate the problems of discontinuity effects and tolerances, different configurations have been evolved that include a new TEM-mode coupling cross section (patent pending). This cross section, which was named the *re-entrant* cross section, offers a number of advantages: 1) its design equations are simple; 2) by its nature tight tolerances are easily held; 3) it can tolerate considerable misalignment of its parts; and 4) experience has shown that it may be joined with conventional strip line end sections without excessive discontinuity effects.

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[1] B. M. Oliver, "Directional electromagnetic couplers," PROC. IRE, vol. 42, pp. 1686–1962; November, 1954.

[2] J. K. Shimizu, "Strip-line 3-db directional couplers," 1957 IRE WESCON CONVENTION RECORD, Pt. 1, pp. 4–15.

[3] J. K. Shimizu and E. M. T. Jones, "Coupled-transmission-line directional couplers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 403–410; October, 1958.

Design Formulas for Re-Entrant Line Couplers

Fig. 1 shows the new re-entrant line coupling cross section. Conductors A and B are coaxial line center con-