Optical Pumping of Microwave Masers*

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Summary—**The application of optical pumping techniques to microwave masers is discussed. It is shown that optical pumping appears to be promising for achieving low noise maser action at very high frequencies and at elevated temperatures. The analysis includes the treatment of optical pumping principles, noise considerations, pump power requirements and maximum signal frequencies. Potential advantages and limitations which can exist when using optical excitation are considered. Finally, the concepts and procedures developed in this paper are applied for illustrative purposes to evaluate the expected performance of a ruby maser.**

Introduction

INTEREST in applying optical pumping techniques to the development of quantum electronic devices has become apparent recently [1], [2], [3]. In particular, the successful demonstration of optically pumped microwave maser action in ruby using a ruby laser as the pump, by D. P. Devor, *et al.* [4], has paved the way for extending present maser technology. This paper is concerned with the requirements and predicted performance of an optically pumped maser. It will be shown that optical pumping methods can be used to achieve maser action with low effective noise characteristics at elevated operating temperatures or very high frequencies.

Although microwave pumped masers have been operated at liquid nitrogen and slightly higher temperatures for some time [5], [6], their performance is not satisfactory for two reasons. First, the gain-bandwidth product is inversely proportional to the temperature and, therefore, is low at elevated operating temperatures. Second, the excess noise temperature of a microwave pumped maser cannot be much lower than the actual bath or operating temperature of the device. However, as will be shown in this paper, by pumping at frequencies in the optical spectrum and at a favorable relaxation time ratio, it is possible to operate a maser without helium cooling while still keeping the noise and gain-bandwidth characteristics comparable to a conventional liquid helium cooled maser. In addition, the present lack of suitable pumping sources for masers operating at very high frequencies can be overcome by applying optical pumping techniques. Although the maser efficiency involved would be small, considerable practical advantages can be obtained.

In principle, the optically pumped maser is identical to conventional three-level masers which have been successfully operated at frequencies between 300 Mc/s and 96,000 Mc/s. The only basic difference is in the optical excitation process employed for obtaining a nonequilibrium distribution in the atomic population density. The basic limitations in the maser mechanism are the appropriate transition probabilities fixed by the inherent material constants. From a knowledge of the transition probabilities it is possible to determine the excess population in an upper state, the effective spin temperature and the pump power requirements of the maser. These properties are analyzed below. The particular case of ruby as the maser material will be considered because of its known optical and microwave properties for photon-spin interaction phenomena.

Optical Pumping Principles

The concepts involved in the optically pumped microwave maser can be treated in a manner similar to an analysis by Bloembergen [7] for a three-level solid state maser. A suitable three-level configuration can be chosen (Fig. 1). The two lower energy levels 1 and 2,

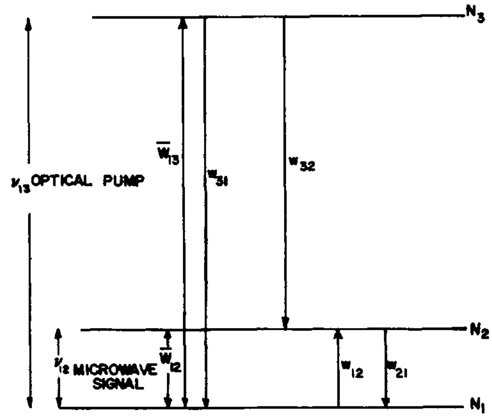

Fig. 1—Energy level diagram of three-level maser using optical pumping.

both belonging to the ground state, are separated by a microwave transition. The third level, 3, is separated from the other two by an optical transition. For such a system, the optical frequency involved is no longer small compared to kT/h at room temperature so that the transition probabilities for the relevant levels are given by

$$w_{12} = w_{21} \exp(-h\nu_{12}/kT) \approx w_{21}(1 - h\nu_{12}/kT)$$

while

$$w_{13} = w_{31} \exp(-h\nu_{31}/kT) \approx 0$$

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and

$$w_{23} = w_{32} \exp(-h\nu_{32}/kT) \approx 0$$

where the w's are the transition probabilities or inverse relaxation times for the specified levels. This information leads to the pertinent steady state maser rate equations for the maser and pump transitions as follows:

$$\frac{dN_2}{dT} = N_1\left(w_{21} - w_{21}\frac{h\nu_{12}}{kT} + \overline{W}_{12}\right) - N_2(w_{21} + \overline{W}_{21}) + N_3 w_{32} = 0 \quad (1)$$

and

$$\frac{dN_3}{dt} = N_1\overline{W}_{13} + N_2(0) - N_3(w_{31} + w_{32} + \overline{W}_{13}) = 0 \quad (2)$$

where the $\overline{W}$'s represent the appropriate induced optical and microwave transition probabilities and N_1, N_2, N_3 are the respective level population densities.

For incomplete saturation between levels 1 and 3, the excess population density can be calculated from (1) and (2), *i.e.*,

$$\frac{\Delta N}{N_1} \equiv \frac{N_2 - N_1}{N_1} = \left[\frac{w_{32}}{w_{21}}\cdot\frac{\overline{W}_{13}}{w_{31} + w_{32} + \overline{W}_{13}} - \frac{h\nu_{12}}{kT}\right] \cdot\left[1 + \frac{\overline{W}_{21}}{w_{21}}\right]^{-1}. \quad (3)$$

The condition for stimulated emission is

$$\frac{w_{32}}{w_{21}} > \left(1 + \frac{w_{31} + w_{32}}{\overline{W}_{13}}\right)\frac{h\nu_{12}}{kT} \quad (4)$$

for $\Delta N > 0$. A simplified expression for (3) and (4) can be obtained by assuming saturation for the pump transition, *i.e.*, $\overline{W}_{13} \gg w_{13} + w_{32}$ or $N_1 = N_3$. Then, for (3),

$$\frac{\Delta N}{N_1} = \left(\frac{w_{32}}{w_{21}} - \frac{h\nu_{12}}{kT}\right)\left(1 + \frac{\overline{W}_{21}}{w_{21}}\right)^{-1} \quad (5)$$

and the corresponding condition for population inversion reduces from (4), to

$$\frac{w_{32}}{w_{21}} > \frac{h\nu_{12}}{kT}. \quad (6)$$

For a maser pumped optically and operating at 10 kMc/s and 300°K, (6) requires the ratio between the optical and microwave transition probabilities to be larger than 2×10^{-3}. For a practical system complete saturation may not be attained. In this case, as can be seen from (4), the required transition probability ratio for the maser material must be correspondingly higher.

It is interesting to compare (6) with the equivalent condition derived by Bloembergen [7] for stimulated emission at ν_{12} with microwave pumping, *i.e.*,

$$\frac{w_{32}}{w_{21}} > \frac{\nu_{12}}{\nu_{32}}. \quad (7)$$

The difference between (6) and (7) lies in the fact that (6) is valid when $h\nu_{32} \gg kT$ and (7) holds for $h\nu_{32} \ll kT$.

From (6) a limiting signal frequency can be defined as

$$\nu^0_{12} = \frac{w_{32}}{w_{21}}\cdot\frac{kT}{h}. \quad (8)$$

Above this frequency the maser ceases to function as a useful device, even with an infinite pumping power. It should be pointed out that the limiting frequency does not increase linearly with temperature, as it would appear in (8). In fact, ν_{12} is a complex function of temperature due to variations in the transition probabilities, particularly w_{21}.

By comparing (6) and (7), it is seen that the value of kT/h in an optically pumped maser is equivalent to ν_{32} in the microwave case because the population of the upper state will be completed depleted at $\nu_{32} > kT/h$. This relationship will also be apparent from the discussion on maser noise [see (12) and (13b)]. The comparison indicates that, as long as the pump frequency is sufficiently larger than kT/h, the advantages of optical pumping in a maser can be realized.

Maser Noise Consideration

Incoherent spontaneous emission of radiation from zero point energy fluctuations sets the lowest limit to maser noise. Noise calculations have been carried out by many authors [8], [9]. In the following, the merits of pumping optically will be discussed by considering only the noise contribution of the maser material.

The excess noise temperature (T_{ex}) is approximately equal to the abolute value of the negative temperature (T_m) which can be achieved by maser operation [10], *i.e.*

$$T_{ex} \approx |T_m|. \quad (9)$$

To determine the value of $|T_m|$, the degree of spin-level inversion is needed. Applying Boltzmann's distribution law to the quasi-equilibrium of a three-level maser and remembering that $kT \gg h\nu_{12}$ for microwaves, the negative temperature can be defined by

$$N_2 - N_1 \approx \frac{N_1 h\nu_{12}}{k|T_m|} \quad \text{or} \quad |T_m| = \frac{h\nu_{12}}{k\left(\frac{\Delta N}{N_1}\right)}. \quad (10)$$

In the case of the optically pumped maser, the relationship between the negative temperature and the operating temperature (T) is obtained from (3) and (10), *i.e.*,

$$|T_m| = T\left[1 + \frac{\overline{W}_{21}}{w_{21}}\right] \cdot\left[\frac{w_{32}}{w_{21}}\cdot\frac{kT}{h\nu_{12}}\,\frac{\overline{W}_{13}}{w_{31} + w_{32} + \overline{W}_{13}} - 1\right]^{-1}. \quad (11)$$

From the above expression, one may deduce that T_{ex} is increased for large values of signal power ($\overline{W}_{21}$) and $h\nu_{12}/kT$ while reduced for large pump power ($\overline{W}_{13}$) and transition probability ratio w_{32}/w_{21} Eq. (11) can be reduced to

$$|T_m| \approx T\left[\frac{w_{32}}{w_{21}}\cdot\frac{kT}{h\nu_{12}} - 1\right]^{-1} \tag{12}$$

if $\overline{W}_{13} \gg w_{31}+w_{32}$ and if $\overline{W}_{21} \ll w_{21}$ for small signal excitation.

In terms of the limiting signal frequency defined by (8), (12) can be written as

$$T_{ex} \approx T\left[\frac{\nu^0_{12}}{\nu_{12}} - 1\right]^{-1}. \tag{13}$$

In the limit of large gain, the excess noise temperature is further reduced to

$$T_{ex} \approx T\frac{\nu_{12}}{\nu^0_{12}} \tag{13a}$$

where

$$\frac{\nu^0_{12}}{\nu_{12}} \gg 1.$$

Thus, the excess noise temperature can be much lower than the operating temperature.

In the case of a microwave pumped maser having a signal transition at ν_{12}, the excess noise temperature can be obtained [10] by substituting the appropriate value of ΔN in (10).

$$|T_m| = T\frac{\nu_{12}(w_{21}+w_{32})}{w_{32}\nu_{32} - w_{21}\nu_{12}} \approx 2T\left(\frac{\nu_{32}}{\nu_{12}} - 1\right)^{-1}. \tag{13b}$$

Thus, with a microwave pump frequency not very much larger than the signal frequency, the excess noise temperature is of the order of the operating temperature. The merits of optical pumping over microwave pumping are apparent by comparing (13) or (13a) with (13b) and will be further demonstrated in the discussion of the ruby maser.

Pumping Requirements

In order to demonstrate the feasibility of applying optical pumping methods to masers, some consideration must be given to the pump power requirements for any proposed atomic system. For a three-level maser, these depend on the characteristic transition probabilities and linewidths.

In a conventional maser pumped with microwaves, all energy levels are not far from being equally populated, even at liquid helium temperature. Therefore, it is necessary to achieve near saturation of the pump level for the operation of the maser. For the optically pumped maser operated at elevated temperature, however, the situation is different. The populations of the signal levels are almost equal, whereas, the upper (pump) level is practically empty. Saturation of the pump level is not necessary for achieving the required excess population between the signal levels.

An order of magnitude estimate of pumping power requirements may be obtained by assuming that the entrant pump light of area (S) is totally absorbed by the maser material and that the linewidth of the pumping transition is $\Delta\nu$. The pump power requirement (P) becomes

$$P = \mu c S.\Delta\nu \tag{14}$$

where c is the velocity of light and μ is the radiation density per unit bandwidth of the pump light.

The value of μ can be calculated as follows. The relaxation process between the pump levels is assumed to be mostly due to spontaneous emission. Therefore,

$$w_{32} \cong w_{31} = A_{31}. \tag{14a}$$

Similarly,

$$\overline{W}_{13} = \mu B_{13} \tag{14b}$$

where A_{31} is the Einstein coefficient for the spontaneous emission and B_{13} is the coefficient for induced emission. The well-known Einstein relationships shows that the ratio of the probabilities for spontaneous and induced emission are related to each other as follows [11]:

$$\frac{A_{31}}{B_{13}} = 8\pi h\left[\frac{\nu_{13}}{c}\right]^3. \tag{14c}$$

(Note that $B_{13}=B_{31}$.) Combining (3) for the excess population ($\Delta N/N$) with (14a–c), the energy density per unit bandwidth required for pumping the maser material becomes

$$\mu = \frac{16\pi h(\nu_{13/c})^3}{\frac{w_{32}}{w_{21}}\left(\frac{\Delta N}{N_1} + \frac{\nu_{12}}{kT}\right)^{-1} - 1}. \tag{15}$$

The required incident optical pump power is given by combining (14) and (15).

$$P = \frac{16\pi h S\Delta\nu \quad \nu_{13}^3/c^2}{\frac{w_{32}}{w_{21}}\left(\frac{\Delta N}{N_1} + \frac{h\nu_{12}}{kT}\right)^{-1} - 1}. \tag{16}$$

As in the case for optimum noise performance, it is desirable to have a large transition probability ratio w_{32}/w_{21} in order to reduce the optical pump power.

From (16) it can be seen that the maximum signal frequency ($\nu_{12}{}^m$) corresponding to a given excess population ratio ($\Delta N/N_1$) and infinite pump power is

$$\nu_{12}{}^m = \left(\frac{w_{32}}{w_{21}} - \frac{\Delta N}{N_1}\right)\cdot\frac{kT}{h}. \tag{17}$$

When the excess population is reduced to zero, the maximum signal frequency reaches the limiting frequency ($\nu^0{}_{12}$) defined by (8).

Expected Performance of a Ruby Maser System

So far the analysis has been kept quite general. To illustrate the significance and implications of the previous discussion, it is appropriate to examine ruby (Al_2O_3:Cr^{3+}) as an example of a particular maser material.

To determine the practical feasibility of an optically pumped ruby maser, the pump power requirements are examined. A typical excess population, $(\Delta N/N_1)=0.1$ per cent, is assumed. The frequency of the exciting transition in ruby at 6929 Å is $\nu_{13}=4.33\times10^{14}$ cps. for liquid nitrogen temperatures. If one considers a characteristic linewidth of 1 kMc/s and an incident beam of 0.3 cm^2 cross-sectional area, the pump radiation density and pump power can be calculated from (15) and (16) using the available experimental data of ruby, including the dependence of spin-lattice relaxation time on temperature and on chromium concentration [12] and the radiative lifetime for the optical transition [13]. The calculated pump power is plotted in Fig. 2 as a function of temperature for three different signal frequencies. The graph shows that optical pumping powers required for a ruby maser of the assumed properties are high but are in the realm of experimental techniques now available. Another interesting observation is the dependence of the signal frequency on the pump power. The lower limit of the signal frequency is set by the linewidth of the pumping transition because the pump fre-

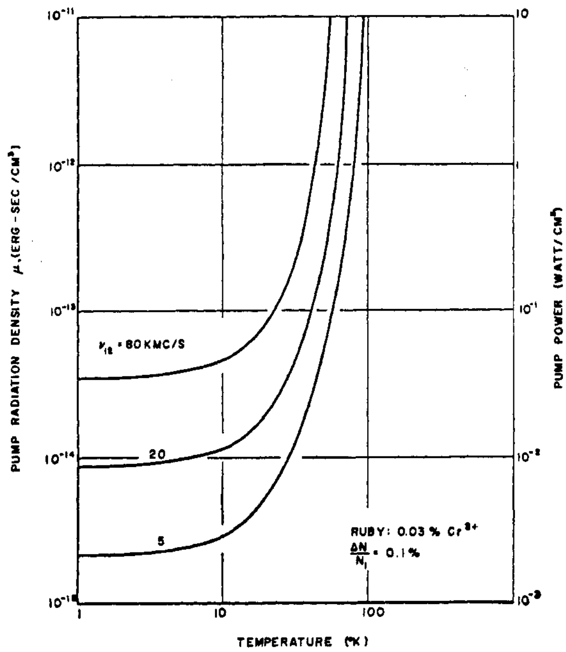

Fig. 2—Pump radiation density and power as a function of operating temperature for optically pumped ruby maser.

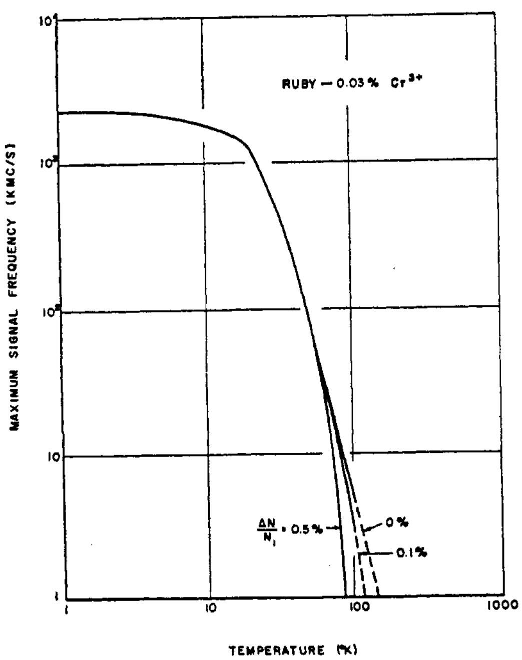

Fig. 3—Maximum signal frequency vs operating temperature for optically pumped ruby maser.

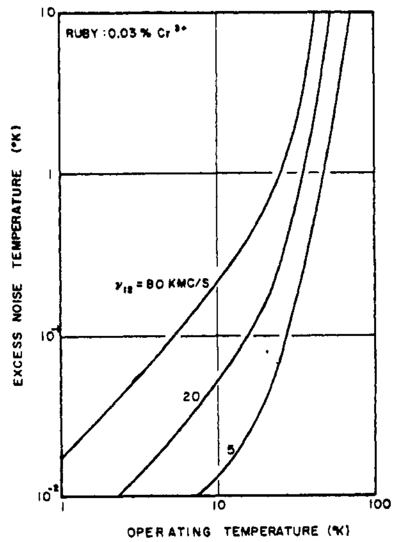

Fig. 4—Noise characteristics of optically pumped ruby maser.

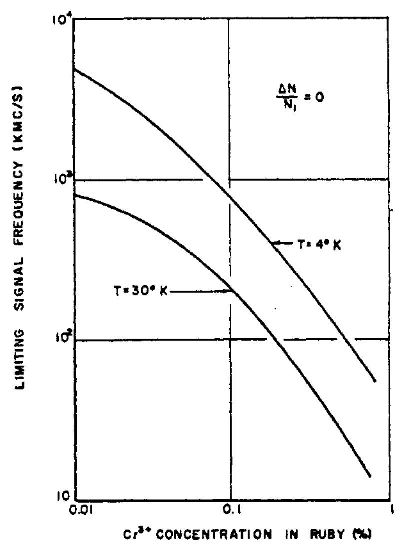

Fig. 5—Effect of operating temperature and chromium concentration in ruby on the upper limit of maser signal frequency.

quency must permit selective pumping in the ground state. From Fig. 2 it is evident that maser action achieved by optical pumping is feasible with ruby as the active material up to liquid nitrogen temperatures.

The dependence of the maximum microwave signal frequency on temperature and on excess population was calculated from (17) and is plotted in Fig. 3. From Fig. 3 and (13) it is possible to predict the maximum operating signal frequency and the excess noise temperature when using optical excitation. In Fig. 4 the predicted values for the excess noise temperature vs operating temperature (T) are shown graphically for three typical signal frequencies. For example, at a bath temperature of 50° K, the excess noise temperature of a ruby maser is 5.32° K for a signal frequency of 20 kMc/s and 1.23° K for a signal at 5 kMc/s.

Fig. 5 depicts the relationship of the limiting signal frequency and, hence indirectly, the noise and pump power as a function of chromium concentration for two characteristic temperatures. It is evident from this graph that even for the most dilute ruby crystal there is an upper limit for signal frequency owing to the reduction of relaxation time at high temperatures.

Conclusions

The application of optical pumping to microwave masers has been examined. This technique appears to be promising for low noise maser action at very high signal frequencies and elevated temperatures, provided the maser material exhibits favorable relaxation characteristics. In the particular case of ruby, low noise performance can be realized for microwave signals at temperatures up to that of liquid nitrogen. The discussion of the ruby maser establishes that a long spin lattice relaxation time at elevated temperatures for microwave frequencies is the prime criterion in the search for new materials suitable for an optically pumped maser. Likewise, a short radiative lifetime for the optical pump transition ($1/W_{32}$) is also a basic requirement in the choice of the pump transition. Since the required optical pump power varies with the third power of frequency, it is preferable to select an energy level scheme having a pump transition with the lowest available pump frequency (provided it is sufficiently larger than kT/h).

It should be pointed out that the effect of cross relaxation was neglected in the above analysis. In practice, cross-relaxation process may become significant, especially for high concentration materials at elevated temperatures. Furthermore, the accuracy of the maser rate equations becomes doubtful with cross relaxation. However, the calculated curves for ruby should indicate the trend in the pumping requirements and maser characteristics and provide a guide in the choice of suitable maser materials.

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