III. OPTICAL AND INFRARED MASERS

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A. STATUS OF RESEARCH

The initial experimental preparations for determination and achievement of frequency stability of the continuously operating gaseous optical maser have been completed. We have begun a series of measurements on the frequency characteristics of two of our He-Ne optical masers. These measurements are made by observation of the radiofrequency beat note obtained by mixing the light output of two independently oscillating masers in the photocathode of a photomultiplier. The frequency stability of the beat note is then studied by means of a spectrum analyzer. The long-term frequency stability of the oscillators is determined essentially by ambient temperature change and microphonic and mechanical stability of the optical resonator. In our present arrangement, the thermal effect results in a frequency drift of a few parts in 10^{10} over a period of 30 seconds. We have still not incorporated an oven to stabilize the temperature of the optical resonator. Our present stability with respect to thermal drift is due to the fairly large mass of the supports of the interferometer plates which respond somewhat slowly to the ambient temperature changes. Our main efforts have been in the direction of eliminating the mechanical instability of the optical resonator.

The masers are mounted on a heavy granite block supported on a few inflated inner tubes of airplane tires. The natural frequency of vibration of the granite on its support is 5 cps. We are in the process of reducing the mechanical resonance of the support through the use of special springs. In the present experiment, the mechanical effects result in sudden changes of the oscillation frequency by approximately one part in 10^{10}. This effect takes place two or three times per second. In the absence of mechanical instability and changes of temperature, the oscillation frequency will be affected by thermal vibration of the support of the interferometer plates. It can be shown that this effect results in random frequency modulation given by $\frac{\Delta\nu}{\nu} = \sqrt{\frac{kT}{YV}}$, where Y is Young's modulus of the support of the plates, and V is its volume. For our masers, the $\frac{\Delta\nu}{\nu}$ that is due to this source is approximately one part in 10^{14}. It should be noted that our observed change of frequency by one part in 10^{10} corresponds to a change of the distance of the two interferometer plates by half an angstrom. Furthermore, this frequency change is several orders of magnitude larger than the actual frequency spread of the maser oscillation. Our present data indicate an order of magnitude improvement of the frequency stability against ambient temperature changes and mechanical vibrations as compared with those reported previously by Javan, Ballik, and Bond.[1] Extensive measurements

of the amplitude of the shock and microphonics in the vicinity of M.I.T. and in the M.I.T. laboratories at Round Hill, New Bedford, Massachusetts, have been carried out. The results indicate that in Round Hill, the amplitude of the shock and microphonics is approximately one hundred times better than in various places in Cambridge. This is due to the particular geological location of Round Hill and the remoteness of that area from heavy industry. We are now in the process of transferring the part of our activities concerned with the determination and utilization of the frequency stability of the optical maser to Round Hill.

A detailed theoretical calculation has been completed in which a new effect for achieving a high degree of efficiency in mixing two optical waves in order to generate a third wave at their difference frequency was explored. The application of this effect in the generation of monochromatic radiation in the far infrared is of particular interest. In this scheme we propose to take advantage of atomic resonances. For this purpose, we propose to mix the two waves in a material that presents two transitions with one common energy level. Furthermore, the frequencies of the two transitions should lie close to those of the two applied waves. In the calculation, the time-dependent density matrix describing the state of the mixing material in the presence of the applied optical frequency (O.F.) fields are solved. The nature of the linewidth and various relaxation processes of the two transitions in the mixing material play important roles. To illustrate this proposal, let us consider an example. Consider two ruby optical masers, one oscillating on R_1 and the other on the R_2 transition. These transitions originate from two excited states of Cr^{+++} which differ in energy by 30 wave numbers. The terminal state in both transitions is the ground state of the Cr^{+++}, and the frequency of R_1 transition is less than that of R_2. Let us subject the output of the two masers to a ruby in which the Cr^{+++} ions are assumed initially to be in their ground state. The presence of the two O.F. fields that are now heavily absorbed because of the resonances of the target ruby, will yield a sizeable coherent mixture of the two excited states of Cr^{+++} ion with its ground state. Such a mixed state then presents an oscillating dipole moment at the different frequency of the two applied O.F. fields, which in turn radiates at the difference frequency. In the limit of large amplitudes of the applied O.F. fields, the algebra involved in the calculation becomes rather formidable.

In the present report we shall give only a brief résumé of the relevant aspects of the calculation. Let us assume that the direction of propagation of the two O.F. fields at the R_1 and R_2 frequencies are such that their respective propagation vectors, $\vec{K}_1$ and $\vec{K}_2$ satisfy the relation $\vec{K}_1 + \vec{K}_d = \vec{K}_2$, where $\vec{K}_d$ is the propagation vector for the third wave at the difference frequency. For the sake of illustration, let us ignore the attenuation of the R_1 and R_2 O.F. fields in the medium. Several limiting cases are encountered. If the applied O.F. fields are not large enough to cause saturation of the optical transition, the power generated at the difference frequency will be given by

$$\frac{P_d}{P_1} \cong \beta_1 \beta_2 \frac{\omega_d^2}{\omega_1 \omega_2} \left(\frac{ME_2T_2}{2h} \right)^2 \frac{L^2}{\lambda_d^2} \cdot \tag{1}$$

In (1), β_1 and β_2 are the absorption coefficients per centimeter of ruby at the R_1 and R_2 transitions and depend on the concentration of the Cr^{+++} in ruby and the full linewidth of the R_1, R_2 fluorescence and the matrix elements involved in these transitions; ω_1, ω_2, and ω_d are the angular frequencies of the R_1, R_2 and the difference radiation frequency; and M is the matrix element connecting the two excited states of ruby. It can be shown that these two excited states allow a magnetic dipole transition. The electrical dipole transition is forbidden between the two levels in the first order; however, we would expect the presence of a sizeable electrical dipole moment in the higher order. In the absence of knowledge of the size of the electrical dipole moment between the two levels, we shall adopt the value $M = 2 \times 10^{-20}$ for an allowed magnetic dipole transition connecting the two levels. E_2 is the amplitude of the applied R_2 O.F. field. L is the length of the target ruby over which the interaction of the two waves takes place and λ_d is the wavelength of the difference frequency radiation. T_2 is a relaxation time defined as the mean time during which an individual Cr^{+++} can interact coherently with the applied O.F. fields without losing its phase. The value of this time is not known. The observed full width of the R_1 and R_2 fluorescence $\Delta\nu_2$ gives only a lower limit of this parameter as $T_2 \geq \frac{1}{\pi\Delta\nu}$. However, the width $\Delta\nu$ is, to a large extent, due to inhomogeneous broadening. In fact, we believe that the distribution of Cr^{+++} over the vibrational states is responsible for the observed width of the R_1 and R_2 fluorescence at room temperature. The transition originates within the same vibrational states and the resonance frequency of the optical transitions is, in turn, dependent on the vibrational quantum number. At liquid-helium temperature for which, essentially, all Cr^{+++} ions are in their lowest vibrational states, $\Delta\nu = 3000$ mc. Therefore, we take $T_2 = \frac{1}{\pi\Delta\nu} = 10^{-10}$ sec, obtained from the observed width at liquid-helium temperature. This value can be safely assumed to be a lower limit of the time T_2 at liquid-nitrogen or room temperatures. In fact, the actual value of T_2 could be considerably longer.

In order to give a numerical value for Eq. 1, let us consider the values of various parameters at a temperature of 200°K. The measured values of β_1 and β_2 at this temperature are each about 0.9 per cm. Equation 1 will give, then,

$$\frac{P_d}{P_1} = 4 \times 10^{-12} E_2^2 \frac{L^2}{\lambda_d^2} \text{ esu.} \tag{2}$$

Let us now compare Eq. 2 with the efficiency of generating the difference frequency with the use of some nonlinear material such as those already used in optical-mixing experiments.[2] For quartz, according to formulation given in Quarterly Progress Report

No. 65 (pages 33-37), we obtain

$$\frac{P_d}{P_1} = 2.5 \times 10^{-20} E_2^2 \frac{L^2}{\lambda^2} \text{ esu.}$$

Notice the sizeable increase in the mixing efficiency which can be achieved by using the resonance effect discussed above.

Equation 1 holds if the amplitude of the fields E_1 and E_2 are not very large and $\left(\frac{\mu E}{2h}\right)^2 T_2 \tau < 1$. In this equation, τ is the radiative lifetime of the ruby R lines, and E is the amplitude of the O.F. field in each single mode, μ is the matrix element of R-line transitions $\sim 10^{-20}$ esu. For $\left(\frac{\mu E}{2\hbar}\right)^2 T_2 \tau \gg 1$ and for $\left(\frac{\mu E}{2h}\right)^2 T_2^2 \ll 1$, Eq. 1 should be multiplied by $\left(\frac{\Delta E}{3kT}\right)^2$, where ΔE is the energy separation of the two upper levels, and T is the operating temperature. At T = 200°K, this reduction factor is approximately 10^{-3}. Under this condition, there is still an improvement of 10^5 in the efficiency of the generation of difference frequency. This observation shows that the dependence of the power of the difference frequency on the two pump powers is not simply proportional to the product of the two powers P_1, P_2.

In the limit $\left(\frac{\mu E}{2\hbar}\right)^2 t^2 \gg 1$, where $t = \frac{1}{\pi \Delta \nu}$, in which $\Delta \nu$ is the observed halfwidth of the inhomogeneously broadened line, the maximum efficiency is obtained when the frequency of the applied O.F. fields is displaced from the undisturbed resonances of the R lines. A discussion of these points will be prepared for publication.

There is a variety of ways and a variety of materials in which these effects may be utilized. For instance, the ruby crystal that serves as the mixing material may be used in the inverted population state. The R_1 and R_2 in this case may be generated in the same crystal that produces the mixing effect. In this case, the difference frequency will radiate at an angle θ with respect to the axis of the ruby, given by $\sin \theta = n_1/n_d$, where n_1 is the index of refraction at the frequency of the R lines, and n_d is that of the difference frequency.

This scheme may also be applied to gases. Then the coherence length determined by the length over which $\vec{K}_1 + \vec{K}_d = \vec{K}_2$ is satisfied can be very long. For instance, if an optical maser is made to operate at two different wavelengths at which the maser transitions involve a common energy level, the same gas may be used to yield the mixing effect. By resonating a long maser interferometer at both of the optical wavelengths, as well as at that of their difference frequency, a detectable radiation can be generated at the new frequency. High magnetic field to split the maser oscillation of a given transition may also be applicable for generating the difference frequency of maser oscillation

within the Zeeman components of the maser levels.

The experimental preparations for generation of the far infrared are in the preliminary stages. A high-power ruby optical maser is being assembled in the Spectroscopy Laboratory, M.I.T. Furthermore, we are in the process of obtaining simultaneous maser oscillation of the two N-lines of ruby[3] which differ in frequency by 80 wave numbers. Our aim in this experiment is to obtain, eventually, the difference frequencies of the two N-line maser oscillation.

An experiment has been completed in which the degree of coherence of radiation across various portions of the ring pattern of a ruby optical maser has been determined. The ring pattern obtained from the output radiation of a ruby optical maser corresponds to that of a Fabry-Perot interferometer, with the radii of the rings given by $R_k = (k\lambda n/d)^{1/2} f$, where k is the order of the Fabry-Perot mode, λ is the wavelength of the emitted radiation, n is the refractive index of the crystal, d is the separation between the parallel reflecting plates (= length of the ruby rod), and f is the focal length of the lens used to focus the far infrared ring pattern.

Experimental evidence shows that the ratios of the intensities radiated in various rings is a property of individual crystals — possibly being related to the homogeneity of each specimen. There is also a marked dependence on power level.

An earlier experiment by Abella and Townes[4] tested the coherence of the output radiation across the face of the ruby crystal. The pattern of the rings was allowed to strike two narrow slits, 2 mm apart, which produced interference patterns that are characteristic of coherent monochromatic light. Thus we concluded that the radiation was coherent across any small region of the ring pattern.

In the present experiments, the diffraction pattern of maser light passing through a thin circular aperture of dimensions suitable for intercepting a particular focused Fabry-Perot ring was examined. At a sufficient distance along the axis of the circular aperture, there was always a bright spot, which indicates that much of the light in the particular Fabry-Perot ring that was investigated was in approximately constant phase all around the ring. Small variations in the alignment of the aperture with the emitted Fabry-Perot rings produced no observed change in intensity along the axis. Hence the variation of phase with distance from the axis of the Fabry-Perot ring system must be rather slow.

Some preliminary experiments with four- and seven-zone Fresnel-zone plates also produced a point of intensity along the axis of the zone plate. However, this was observed to be relatively less intense than that for a thin-ring plate, so that no great strengthening of the central diffraction spot was actually achieved.

The effect of variations in the densities of silvering on the reflecting faces of the crystals was also tested. We thought that a more reflective coating would produce greater coupling between all of the angular modes because of the increase of the average

path length of the light in each mode. There was no observed difference in the resulting relative intensities diffracted to the axis of the thin circular aperture, or of the zone plates. There is evidence, though indirect, that most of the radiation striking the transmitting ring, rather than only a small part, was of constant phase.

The experiments just completed indicate that much of the radiation around the periphery of a Fabry-Perot ring from a ruby maser beam is of constant phase all around the ring. Variation of phase from mode to mode is probably not rapid. For a constant input power, relative intensities of radiation in the various Fabry-Perot rings is a function of the homogeneity of the crystal involved for a constant input level. These experiments give promise of greatly narrowing the beam of a high-power ruby maser by suitable optical techniques. With more perfect crystals and circular optical plates to correct the variation of phase from ring to ring, we may be able to refocus much of the radiation from the ruby optical maser so that the dimensions will be determined only by diffraction, the diffraction limit being approximately one-half the wavelength of the light. Correspondingly, the beamwidth will be limited only by diffraction.

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References

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