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Zeeman Effects in the Helium-Neon Planar Laser

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In this paper, the effect of stray or applied magnetic fields on the modes and polarization of the planar laser output is considered. For weak fields the splittings are small compared to the Doppler broadening of the Ne laser transition, but the polarizations, or labeling of the photons available in the Zeeman transitions, allow simultaneous oscillation in different modes at frequencies within the same natural linewidth of the Ne atoms in the vicinity of a given axial resonance. Strong low-frequency beats are observed and arise from a splitting of a single axial resonance into two oscillations with different polarizations, which are pulled towards the centers of the respective lines. Such low-frequency beats also give rise to a splitting of the 120-Mc/sec axial mode beats. The multiplicity of low-frequency beats observed, particularly for small magnetic fields and high power levels, is due to similar effects from a number of axial modes. At higher magnetic fields relaxation oscillations similar to those which occur in the ruby laser are in evidence.

RECENTLY Bennett[1] has discussed mode coupling, or nonlinear effects, in the helium-neon laser which results in a power-dependent frequency splitting of the 120 Mc/sec beats which occur between adjacent axial modes of the planar interferometer. We also have observed a similar splitting of such beats into components with nominal 50-kc/sec frequency intervals. However, in addition to the 120-Mc/sec beats we have observed very strong low-frequency beats, extending from about 10 kc/sec to 200 kc/sec. Apparently, the laser can oscillate simultaneously in modes with low-frequency separations as well as in a number of different axial modes and in associated off-axis or TEM_{mnq} modes. Such low-frequency beats can also lead to a splitting of the 120-Mc/sec axial beats and provide additional information on the number of simultaneously oscillating axial modes. Therefore, the past conclusions deduced from the splitting of the 120-Mc/sec beats may be in error regarding the number of simultaneously oscillating axial modes.

These low-frequency beats and the definite polarizations observed in the planar laser output are due to the presence of a stray or an applied magnetic field. Such a field will remove the degeneracy of the upper $J=1$ level and the lower $J=2$ level of the laser transition. For axial magnetic fields the transitions $\Delta M=\pm 1$ give oppositely rotating, circularly polarized laser output beams, and for fields perpendicular to the laser axis the transitions $\Delta M=0$, ± 1 give laser radiation polarized parallel and perpendicular to the field, respectively. This agrees with our observations, and the specific polarizations of the planar laser output which have been reported[1], most probably are due to stray magnetic fields around the laser. Furthermore, the different polarizations of the photons available in the Zeeman transitions supply a mechanism whereby simultaneous laser oscillations can occur at frequencies within the same natural linewidth of the neon atoms in the vicinity of a given axial resonance. Such labels on the individual photons available explain the beats previously observed at 1 Mc/sec in the helium-neon laser and, also, the very low frequency beats which we have observed. The Zeeman transitions preserve their identity even when the frequency splittings are small compared to the width of the Doppler broadened laser transition.

The upper trace of Fig. 1 shows axial mode beats at 120 Mc/sec and, on the left, a beat at 119 Mc/sec between TEM_{00q} and TEM_{10q} modes, with a stray magnetic field of some 4 Oe perpendicular to the laser axis. A similar beat at 121 Mc/sec is also produced but is not visible because a Nicol prism, passing only vertical polarization, has been inserted into the laser beam. This beat is due to modes with orthogonal polarizations and reappears when the Nicol prism is rotated, having a maximum amplitude at 45° orientation. Similarly, the left-hand beat at 119 Mc/sec is due to modes with

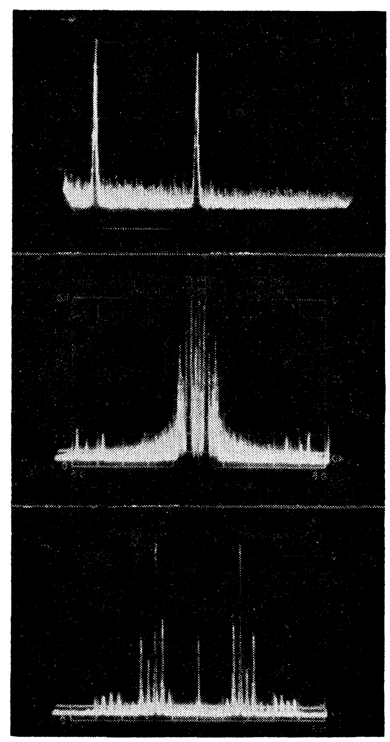


FIG. 1. Upper—polarization of axial and off-axis mode beats at 119 Mc/sec, 120 Mc/sec, and 121 Mc/sec. Middle—frequency sweep nominally ±1 Mc/sec, showing 1-Mc/sec beat between an axial mode and its associated TEM_{10q} mode. Also strong low-frequency beats at 10 kc/sec–200 kc/sec. Lower—frequency sweep ±250 kc/sec, showing modulation of low-frequency beats with an axial magnetic field of 30 oe.

[1] W. R. Bennett, Jr., Phys. Rev. **126**, 580 (1962).

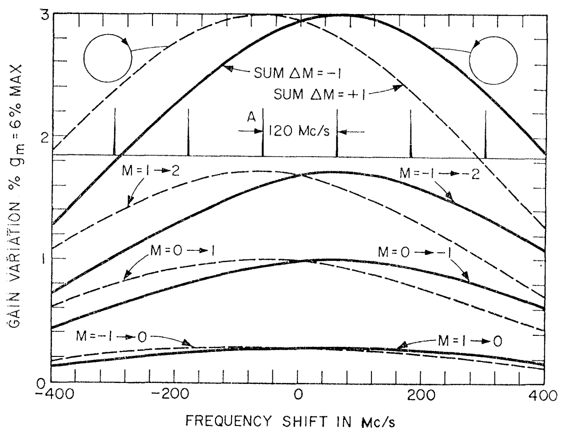


FIG. 2. Zeeman splitting of Ne laser transition for an axial magnetic field of 30 Oe.

vertical polarizations, as is the center beat at 120 Mc/sec. Although the center beat sometimes exhibits a more complicated behavior upon rotating the Nicol prism, due to mode-splitting effects, the polarizations of the modes are linear and either parallel or perpendicular to the magnetic field. With a magnetic field along the laser axis, only modes of right- and left-handed circular polarization are present, and beats between modes of circular polarizations are not seen unless a Nicol prism with arbitrary orientation is inserted into the beam.

The center trace, also taken with a magnetic field on the laser, shows 1 Mc/sec beats between axial TEM_{00q} and off-axis TEM_{10q} modes and also a number of the strong low-frequency beats referred to above. Such low frequencies cannot be due to beats between axial and off-axis modes, and we feel that they arise from a splitting of a single axial resonance of the interferometer due to a Zeeman splitting of the Doppler broadened lines. The lower trace shows one of the frequency patterns obtained with an axial magnetic field of some 30 Oe on the laser. A Nicol prism was interposed in the beam and all beats disappeared when it was removed, showing that the beats are due to modes of opposite circular polarization. The mean beat frequency is around 80 kc/sec, and the very regular spacing and interval between the frequencies indicate that the laser output, on one of the modes at least, is modulated at a frequency of some 10 kc/sec. Similar results were obtained with magnetic fields perpendcular to the laser axis.

Figure 2 shows the Zeeman splitting and frequency shifts of the laser transition for an axial field of some 30 Oe. A single-pass gain of 6% was assumed before splitting, and the various transitions have been weighted by the spontaneous transition probabilities.[2] A gain variation given by[1]

$$g(\nu)=g_m \exp\left[-\left(\frac{(\nu_m-\nu)}{0.6\Delta\nu_m}\right)\right]^2 \qquad (1)$$

was used with $0.6\Delta\nu_m=500$ Mc/sec. The various $\Delta M=+1$ transitions have been summed, similarly for the $\Delta M=-1$ transitions, corresponding to photons of right- and left-hand circular polarizations. Axial resonances of the interferometer are also indicated; these, and not the Zeeman splittings, primarily determine the frequencies observed. In addition, second-order variations arise from frequency pulling effects due to the medium, as discussed by Bennett. There are now two Doppler-broadened lines, and these provide the means whereby a single axial resonance can give rise to two closely spaced frequencies, since modes with opposite polarizations are pulled toward the centers of the respective lines.

Thus, if the interferometer resonance were at A, no pulling of the right circular polarized oscillation would occur, but the left circular polarized oscillation would be pulled by an amount[1]

$$\Delta\nu=(\Delta\nu_c/f)0.28g_m \sin\left(\frac{\nu_m-\nu}{0.3\Delta\nu_m}\right). \qquad (2)$$

Here $\nu_m-\nu=120$ Mc/sec, $\Delta\nu_c=1$ Mc/sec, $\Delta\nu_m=800$ Mc/sec; and hence for $g_m=f$, the loss per pass, we have $\Delta\nu=130$ kc/sec, in general agreement with the observed magnitude of the low-frequency beats. Also, since these beats arise from the same axial mode they will be strong, particularly with small magnetic fields. The beat frequency will vary with the axial mode number, hence accounting for the observed multiplicity of such beats.

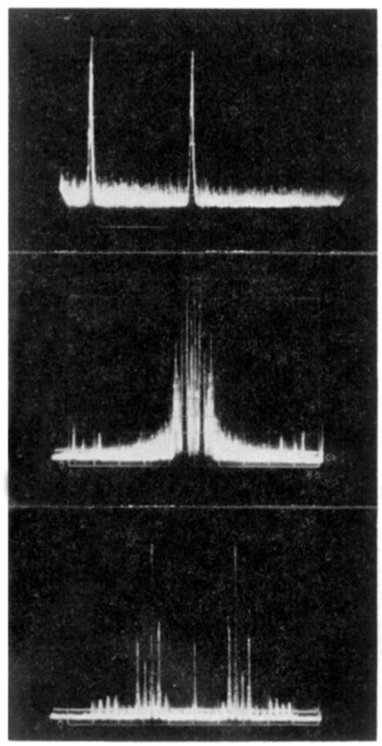
The periodic modulation effect in Fig. 1, which occurred for an axial field of 30 Oe, seems due to one of these oscillations approaching the threshold as the magnetic field is increased. Relaxation oscillations similar to those observed in the ruby laser[3] then occur, the spectrum of which beats with the other continuous oscillation to give the observed modulation spectrum. Results on transients and oscillation pulses in masers[4] indicate that relaxation oscillations at frequencies around 10 kc/sec are feasible. Such beautiful modulation patterns at low frequencies are indicative of the narrow linewidth of the laser and of its use in spectral analysis. Hole repulsion effects[1] occur between different axial modes within the same linewidth; these will affect the low-frequency splitting of a given axial resonance. These matters are under further investigation; meanwhile, such pronounced effects caused by small magnetic fields should be considered in evaluating mode phenomena in gas lasers.

The important efforts of W. Proskauer in the mechanical design of the laser and those of D. Jacques on instrumentation are gratefully acknowledged.

[2] E. U. Condon and G. H. Shortley, The Theory of Atomic Spectra (Cambridge University Press, New York, 1959), p. 387.

[3] R. J. Collins, D. F. Nelson, A. L. Schawlow, W. Bond, C. G. B. Garrett, and W. Kaiser, Phys. Rev. Letters 5, 303 (1960).

[4] H. Statz and G. deMars, Quantum Electronics—A Symposium, edited by C. H. Townes (Columbia University Press, New York, 1960), p. 530.



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