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Coherence Effects in Gaseous Lasers with Axial Magnetic Fields. II. Experimental*

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The rotation of the plane of polarization with an axial magnetic field on a short single-mode He-Ne planar-type laser has been studied experimentally. The study is concerned with regions of magnetic field where the beat frequency between the orthogonal circularly polarized oscillations approaches zero. A mutual synchronization of these otherwise independent oscillations then occurs over a range of magnetic field, resulting in a single frequency of oscillation in which the polarization remains linear but rotates. In near-zero magnetic field, rotations up to $\frac{1}{4}\pi$ are observed and may occur with magnetic fields less than 0.1 G. Results are given on the rotation versus magnetic field as a function of the laser intensity, the cavity tuning within the Doppler linewidth, the total gas pressure, and the anisotropy in the cavity losses. The observed rotation increases with the intensity and decreases with cavity detuning, with increasing total gas pressure, and with increasing anisotropy in the cavity Q. On attaining a rotation of $\frac{1}{4}\pi$, a transition region of magnetic field between the linear and circularly polarized regions is observed. The beat signal from the orthogonal circularly polarized waves then shows a high harmonic content due to transient behavior, which gives way to a single beat as the magnetic field is increased. Other such coherence regions are observed at magnetic fields of 10 G or more, where the observed beat frequency again approaches zero. Here the polarization again becomes linear and rotations similar to those in near-zero magnetic field are observed.

1. INTRODUCTION

In an earlier paper[1] we have discussed the rotation of the plane of polarization which occurs when small axial magnetic fields are applied to gaseous lasers. Some experimental results were presented, which showed that a rotation of $\pm 45°$ occurred when an axial magnetic field of some 0.1 G was applied to a short planar type He-Ne laser operating on the 1.153-μ Ne transition. Furthermore, the rotation of the plane of polarization with magnetic field was found to be dependent on the intensity of the laser oscillation, and on the position of the resonant frequency of the cavity within the Doppler linewidth of the transition. Subsequently, a more extensive theoretical analysis[2] has explained the dependence of the rotation on the laser intensity and on the cavity tuning, and has also predicted a dependence on the anisotropy of the Q values of the cavity.

This paper gives more precise and detailed experimental results on the observed beat frequencies and also on the rotation of the plane of polarization with magnetic field, specifically as a function of the various parameters of interest, such as oscillation intensity, cavity tuning, anisotropy in the Q values, and the total gas pressure. In addition, some results are given for the transition region between the linearly and circularly polarized regions, where the coherence between the oppositely circularly polarized oscillations starts breaking down. Also discussed is another coherence region, where the polarization is again linear, and which occurs at much higher magnetic fields, of the order of 10 G or higher depending on conditions. The results reported here were obtained on another more precisely controlled model of a short planar laser, with improved reflector adjustments, and which incorporated a thermal tuning element whereby the length of the laser cavity can be changed. The laser, which again can be operated in a single mode because of its short length, can thus be tuned across the Doppler linewidth of the transition, and the rotation investigated as a function of cavity tuning. The discharge tube in the laser was carefully screened by a box of magnetic shielding material which eliminated the effects of the earth's magnetic field, and of any other stray magnetic fields. Small axial magnetic fields were then applied by means of a solenoid centered on the axis of the laser and also inside the magnetic shielding box.

One generally observes than the polarization of the laser radiation in zero magnetic field is linear and almost always in one of two orthogonal preferred directions. These preferred directions are determined by small anisotropies in the laser cavity, such as in the reflectors. Also, as the present laser was tuned across the Doppler linewidth, an instantaneous jump in the direction of polarization occurred at certain tuning positions. In most of the results reported here the reflector orientation was such that this jump occurred close to and slightly to the high-frequency side of the Lamb dip.[3] On applying small magnetic fields to this laser a rotation of the plane of polarization was again observed. In accord with previous results,[1] the rotation for a given magnetic field was larger at higher oscillation intensities, and also when the cavity was tuned close to the center of the Doppler line. When the 90° jump in the polarization was close to the line center, the region of sharpest rotation was at this position rather than at line center. In addition to the changes which occur in the slope of the rotation versus magnetic field curve, its shape is also affected by the cavity tuning, especially at lower levels of oscillation intensities. With all other conditions kept constant, the

* Supported by the Lockheed Independent Research Funds.
[1] W. Culshaw and J. Kannelaud, Phys. Rev. 136, A1209 (1964).
[2] W. Culshaw and J. Kannelaud, preceding paper, Phys. Rev. 141, 228 (1966). Hereafter referred to as Part I.
[3] W. E. Lamb, Jr., Phys. Rev. 134, A1429 (1964).

rotation varied inversely with the amount of anisotropy in the cavity Q. All of these observed effects are in general agreement with the theoretical results deduced in Part I.

It was also found that the polarization does not change abruptly from linear to circular when the magnetic field is increased. There is a transition region of about 1 G after the circularly polarized components first appear, and in which the beat signal from the laser output contains many harmonics instead of a single distinct beat frequency as one would expect when two oppositely circularly polarized sinusoidal waves are present.

2. THE EXPERIMENTAL ARRANGEMENT

A short He-Ne laser, with a reflector spacing of 21.25 cm and operating at 1.153 μ was used in these experiments. This reflector spacing results in a frequency separation of 706 Mc/sec between axial modes and assures single-mode operation under most operating conditions. The laser tube had a bore of 3 mm, and the discharge was 11.5 cm long, excited by a rf source at 52.5 Mc/sec. In addition to the usual adjustments for angular alignment of the reflectors, a thermal expansion wafer was incorporated in the structure which made it possible to change the reflector spacing by small amounts, thereby changing the cavity resonance frequency. This wafer consisted of an aluminum disk 0.08 in. thick, sandwiched between quartz plates for heat insulation. A layer of fine copper wire was wound on the wafer which could be heated by passing a small current through it.

A solenoid of 3.2-cm diameter and 14.6-cm length was placed around the laser tube for applying axial magnetic fields. The ends of the solenoid were overwound to produce better uniformity of field over its total length. The field uniformity was better than 2% over most of the active discharge length, decreasing to 6% over the last 0.5 cm of the discharge. A field of about 18 G/A was obtained with this solenoid. The discharge tube and solenoid were totally enclosed in a $3\frac{1}{2}$-in.$\times$7-in mu-metal magnetic shielding box, the only holes being those through which the discharge tube passed. This enclosure shields the laser tube from the earth's magnetic field and from any other external magnetic fields, and at the same time shields the metal parts of the laser structure from the stray fields of the solenoid. Very effective shielding was provided by the box. No magnetic field could be detected inside the box, using a gaussmeter set at a range of 0.1-G full scale, except very close to the holes where a field of less than 5 mG could be measured for a short distance.

3. POWER OUTPUT AND POLARIZATION IN ZERO MAGNETIC FIELD

We are interested in studying the rotation of the plane of polarization of the laser output with an applied axial magnetic field, and as a function of several parameters,

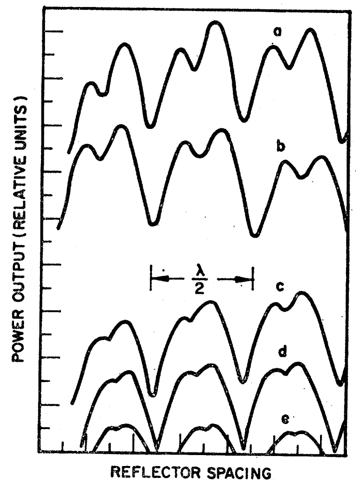


FIG. 1. Power output of laser versus cavity tuning for various levels of rf excitation of the laser. (a) rf excitation 15 W, relative laser intensity 1.23. (b) rf excitation 8 W, relative intensity 0.9. (c) rf excitation 6 W, relative intensity 0.45. (d) rf excitation 4.5 W, relative laser intensity 0.2. (e) rf excitation 4.0 W, relative laser intensity 0.08.

for example, the tuning of the cavity resonance frequency with respect to the Doppler-broadened gain curve, the oscillation intensity, and the gas pressure. However, it is of interest to first investigate the oscillation intensity and the polarization characteristics as a function of cavity tuning in the absence of a magnetic field. This was done by tuning the cavity by applying a constant current to the expansion wafer, and recording the resulting output of the laser as a function of time. The results are shown in Fig. 1, where one observes the changes in output as one tunes each successive resonance of the laser cavity over the Doppler line. The now familiar Lamb[3] dip is observed when the resonance is tuned to the center of the line. Unfortunately, the temperature of the expanison wafer does not vary linearly with time in such a procedure, so an accurate scale factor for the frequency tuning cannot be conveniently established. A few seconds after the application of the heating current to the wafer, however, a linear relationship is approximately achieved (equal distance between successive maximum and minima of the output curves) and an approximate frequency scale may be established. It is seen from Fig. 1 that parallelism is not accurately maintained between the reflectors as the spacing between them is changed by the wafer (change in output between consecutive resonances). This imperfection in the system, however, is not of much concern for present applications.

In curves A and B, Fig. 1, the double peaks near the line center are separated by about 280 Mc/sec, in curves C and D by 210 and by 180 Mc/sec, respectively, and in curve E by 135 Mc/sec. From this separation between the double peaks it is possible to calculate the excess of the population inversion over that required for threshold of oscillation, and thereby relate each intensity level to threshold conditions. It should be noted here that the separation of the double peaks in our case is much larger than that reported by McFarlane *et al.*[4] and Szöke *et al.*[5] in similar experiments, indicating that much higher power levels are involved in our case. This is to be expected, since their lasers were of much greater length, thus necessitating operation at reduced power levels in order to obtain single mode operation. In the experiments reported by McFarlane *et al.*,[4] the maximum spacing is about 120 Mc/sec, in those reported by Szöke *et al.*,[5] it is about 70 Mc/sec. Natural neon (about 91% Ne^{20} and 9% Ne^{22}) was used in this part of our experiments which may account for the unequal peaks. It was observed however, that the relative magnitude of the peaks is also somewhat dependent on reflector alignment.

When one axial mode is tuned to the center of the Doppler-broadened line the next one being 706 Mc/sec removed will have about one-tenth of the gain of the mode at the line center, and single-mode operation may be safely assumed. When the modes are about 350 Mc/sec removed from the line center, thus giving a symmetrical placement of the modes, the gain is only reduced to 60% of the maximum and two modes may simultaneously oscillate at high excitation levels. This may be seen to be the case in Fig. 1 where it is seen that at high-power levels the laser never stops oscillating between two successive resonances. It is further observed that in the troughs between two resonances the laser output is no longer linearly polarized as it should be in zero magnetic field and in single-mode operation.

In addition to variations in the power output with cavity tuning, changes in the plane of polarization of the output have been observed. Specifically, a sudden 90° jump in the direction of polarization occurs at certain fixed points on the Doppler curve. The position of this jump depends on the anisotropies in the reflectors and on the relative orientation of these anisotropies in the two reflectors. In zero magnetic field the laser output is linearly polarized and almost always in one of two orthogonal preferred directions. Minor deviations occur from these directions with reflector alignment, but a very dominant set of orthogonal preferred directions exists. When one of the reflectors is rotated with respect to the other one the preferred directions rotate to a new orientation. In part of our experiments one of the reflectors was rotated by 90° which caused the preferred directions to rotate, changed the position on the Doppler curve where the "polarization flip" occurred, and also increased the anisotropy in the cavity Q. Most of the results presented here were obtained with the orientation which yielded the smaller anisotropy in the cavity Q. For this orientation the 90° polarization flip always occurs at a frequency slightly higher (10–50 Mc/sec) than the Lamb dip. Another 90° rotation is seen to take place around 350 Mc/sec from the line center, in the region where two modes are expected to oscillate. Both these rotations are displayed in Fig. 2, where the dashed trace shows the laser power output when the beam is passed through an analyzer, and the solid trace shows the power output traced simultaneously from the other end of the laser without an analyzer inserted, to serve as a reference of the position on the Doppler line.

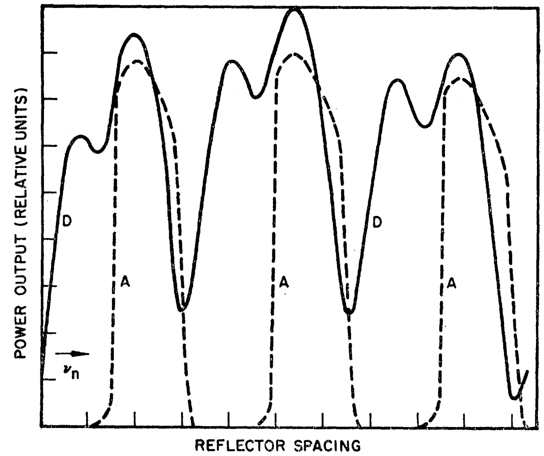


FIG. 2. Position of the 90° polarization flip on the Doppler linewidth. Curves relative only. D—laser intensity when tuned over linewidth. A—output through an analyzer oriented at 90° to the initial polarization.

When one of the reflectors was rotated 90° the position of the polarization flip was shifted to about 180 Mc/sec from the line center. The position of the polarization flip does not stay absolutely fixed for a given reflector orientation. It occurs at a slightly higher frequency when the frequency is scanned in a positive direction and at a lower frequency when the frequency scan is negative (about 10–15 Mc/sec). Likewise, for the reflector orientation which gave the lower anisotropy in the cavity Q, shifts up to 50 Mc/sec were observed with changes in oscillation intensity. For the change to an orthogonal orientation of one of the reflectors even more drastic changes were observed with oscillation intensity.

From Fig. 2 we note that the 90° rotation of polarization near the Lamb dip is very rapid, possibly an instantaneous jump, whereas the rotation near the minima of the power curve is much slower. In the latter region, however, the polarization is not linear, indicating that an apparent rotation might take place due to one axial mode bing slowly reduced in intensity and ceasing to oscillate, while the next one in a perpendicular direction takes over. It thus appears that there is a preferred direction of polarization when the cavity resonance is tuned to the low-frequency side of the polarization flip and a preferred direction perpendicular to the first one, when the resonance is on the high-frequency side. Although the preferred directions are obvioulsy due to

[4] R. A. McFarlane, W. R. Bennett, Jr., and W. E. Lamb, Jr., Appl. Phys. Letters 2, 189 (1963).
[5] A. Szöke and A. Javan, Phys. Rev. Letters 10, 521 (1963).

small anisotropies in the reflector coatings, the observed polarization changes need further elucidation.

4. ROTATION OF POLARIZATION WITH MAGNETIC FIELD

Because of the relatively rapid drift of the laser due to thermal changes it is impossible to obtain satisfactory measurements of the rotation of polarization by a point by point method where the direction of polarization at a given magnetic field is determined by rotating the analyzer. For that reason the measurements were performed by leaving the analyzer fixed and recording the output of the photodetector as the magnetic field is swept. This enabled us to sweep through the whole required range of the magnetic field quite rapidly and thereby greatly reduce the effects of drift in the laser frequency.

The current from the photodetector is proportional to the intensity of the incident light wave. Thus, when an analyzer is placed in front of the photodetector the photocurrent will be proportional to $E^2 \cos^2\theta$, where E is the electric-field amplitude of the wave, and θ is the angle between the direction of polarization of the wave and the direction of maximum transmission of the analyzer. If we set the analyzer initially at 45° with the direction of polarization in zero magnetic field, and then sweep the field to cause the polarization to rotate plus or minus 45°, the intensity incident on the detector will vary between 0 and 100%. Furthermore, because $\cos^2\theta$ varies linearly with θ around 45°, we find that for small magnetic fields and rotations up to about 25° the detector current is very closely directly proportional to the angle of rotation. As the rotation increases and approaches 45°, $\cos^2\theta$ is no longer linear in θ and the intensity versus magnetic field curve no longer has the shape of the rotation versus magnetic field curve. At 18° rotation the error is about 5%, at 25° rotation about 13%, increasing more rapidly from there on.

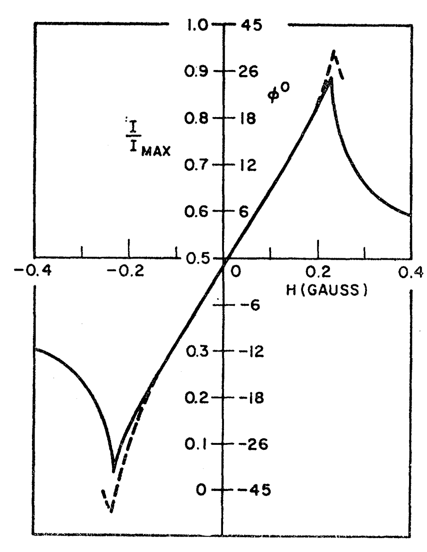


FIG. 3. X-Y recorder plot of the rotation versus magnetic field. Note the true shape, shown dashed, of the ϕ versus H curve if plotted with a linear ϕ scale.

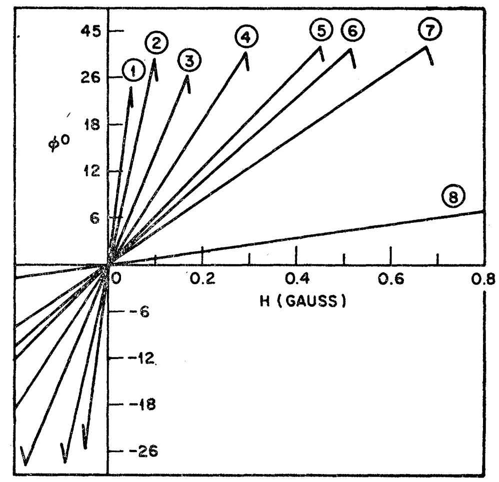


FIG. 4. Experimental plots of the rotation of polarization versus magnetic field. Rf excitation 15 W, relative laser intensity 10. No. 1, near the flip region. No. 2, near Lamb dip. No. 3, on peak on high-frequency side, $\Delta f = -160$ Mc/sec. No. 4, on low-frequency peak $\Delta f = 120$ Mc/sec. Nos. 5–8, on low-frequency side of dip at 200, 220, 240, and 300 Mc/sec, respectively.

Figure 3 shows a typical recorder curve of rotation versus magnetic field obtained in the manner described above. The ordinate axis has both a calibration scale for intensity and one for the rotation in degrees. It should be noted that the scale for rotation in degrees is not linear above 18°, a compression of the scale is seen to take place between that value and 45°. The broken line shows the shape of the rotation curve if a linear scale for rotation is used. It is of interest to note that this curve is in good agreement with the types of theoretical curves shown in Figs. 7, 8, and 9 of Part I. At the point where the curve suddenly reverses slope, circularly polarized low-frequency beats appear, indicating that some coherence is being broken down. As the analyzer now absorbs half of the intensity that is circularly polarized, the photodetector output is seen to suddenly drop. The rotation, of course, still increases up to 45° but cannot be deduced from these curves beyond the point where the low frequency beats appear. The output is seen not to change abruptly from linear to circular beyond this point but a gradual changeover takes place as the magnetic field is increased from 0.2 to 0.8 G. A certain amount of asymmetry is noted in the curve in Fig. 3. This is frequently due to small drifts in the laser tuning during the measurement, however, at times a consistent asymmetry has been observed. Because of the difficulty of eliminating the erratic drifts a more detailed investigation of this asymmetry was not undertaken at this time.

Figures 4 and 5 display tracings of recordings of the kind described above, taken at two different oscillation intensities and at various settings of the cavity tuning

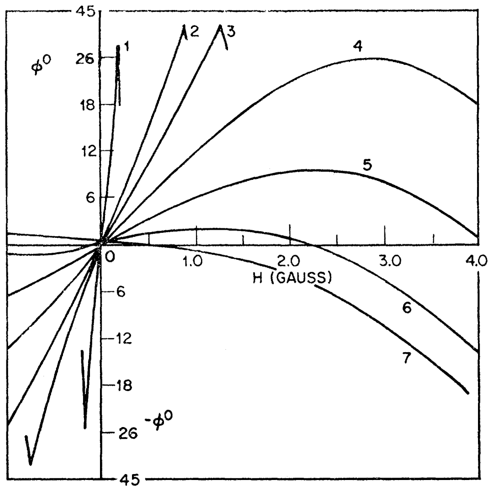


FIG. 5. Experimental plots of the rotation of polarization versus magnetic field. Relative laser intensity 4.7. No. 1, at line center, $\Delta f=0$. No. 2, $\Delta f=110$. No. 3, $\Delta f=160$. No. 4, $\Delta f=230$. No. 5, $\Delta f=270$. No. 6, $\Delta f=300$. No. 7, $\Delta f=320$ Mc/sec.

with respect to the center of the Doppler line. The reflector orientation is that which produces the smaller anisotropy in the Q values. It is noted that the maximum slope of the rotation versus magnetic field curve occurs (see Fig. 4) when the cavity is tuned to the point where the polarization flips 90° in zero field, and that the slope steadily decreases as the cavity resonance frequency is detuned to either side from this point. When the resonance is far from the line center the slope is very small. It is also noted from Fig. 4 that for a given detuning from the line center, the rotation is faster on the high-frequency side.

Comparing Figs. 4 and 5 we see that the rotation for a given magnetic field decreases when the oscillation intensity is decreased. This effect is more pronounced when the resonance is tuned off the line center than near the center. At lower oscillation intensities, as we detune the resonance from the line center, the rotation becomes progressively slower and the maximum rotation is not reached with a magnetic field up to 1 G. In Fig. 5 the magnetic field sweep is extended to 4 G. We note that with cavity tuning 230 Mc/sec or more off the line center the rotation no longer shows the previous linear relations with magnetic field but rather exhibits an "S-curve" type dependence, where the rotation actually reverses direction during one positive-going magnetic field sweep. Here again, the polarization stays linear over the whole length of the S curve and low-frequency beats appear at the point where the abrupt change of slope in the curves occurs (not shown in the figure). When the intensity of oscillation is decreased further the S curve shifts closer to the line center and as one tunes the resonance farther from the line center, the rotation curves become linear again, but with a negative slope. It is seen from Figs. 4 and 5 that the rate of rotation of the polarization increases with increasing oscillation intensity. To facilitate a better comparison, the rotation is plotted with oscillation intensity as a parameter in Fig. 6, the cavity resonance being tuned to the line center.

The rotation of the polarization with magnetic field is dependent on the lifetimes of the states involved. It is therefore to be expected that a pressure dependence may be observed in the rotation. The pressure effect is displayed in Fig. 7 where the rotation is shown for the two pressures, 4 and 2 mm. A higher rate of rotation is observed at the lower pressure even though the oscillation intensity is 3.5 times lower in this case (highest that could be obtained with the available rf excitation). This would be expected because of the greater effective linewidths involved at the higher pressures. It should be noted here that the true value of the pressure in the laser tube is somewhat in doubt. It has been observed that after the laser is filled with gas and the rf excitation turned on, no oscillation is observed for a short period even though the reflectors may be perfectly aligned. After a few minutes, however, a weak oscillation starts, and slowly continues to grow until a maximum is reached. In a similar manner, when the rf excitation is suddenly increased, for example, the laser output may drastically drop at first, but then slowly increase to its previous value over a period of several minutes. It is postulated that this effect is due to a change in the gas temperature in the laser tube. If the gas temperature in the laser tube is increased, the density of the atoms will decrease as atoms are driven to colder parts of the vacuum system to provide a uniform pressure throughout the system. Because of this effect the pressure values listed must be considered as approximate.

In order to study the effects of reflector anisotropies, one of the reflectors was rotated 90° in one part of our

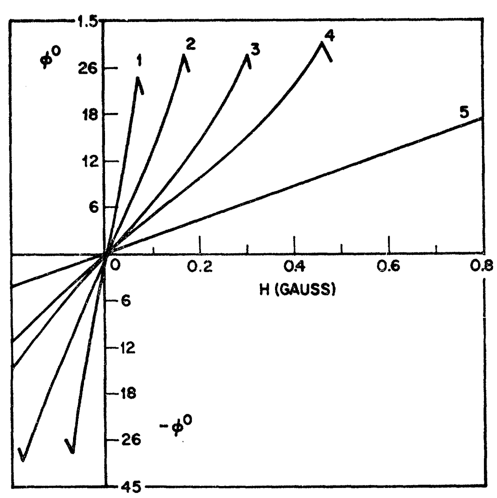


FIG. 6. Observed dependence of the rotation of polarization with magnetic field on the laser intensity. Laser cavity tuned to the Lamb dip. No. 1, relative intensity $I=13.4$, No. 2, $I=11.7$. No. 3, $I=6.6$. No. 4, $I=4.6$. No. 5, $I=3.0$.

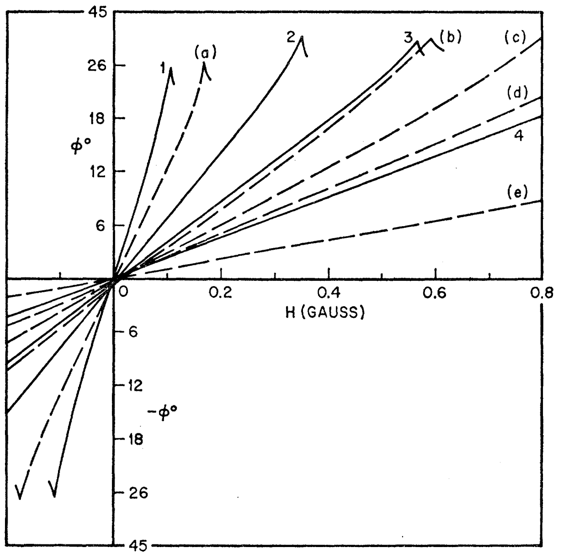


FIG. 7. Pressure dependence of the rotation of polarization with magnetic field. Full curves, total pressure 2 mm Hg, rf excitation 50 W, relative intensity 4.4. No. 1, $\Delta f=0$. No. 2, $\Delta f=110$. No. 3, $\Delta f=220$. No. 4, $\Delta f=270$. Dashed curves, total pressure 4 mm Hg, rf excitation 10 W, laser intensity 15. (a) $\Delta f=0$. (b) $\Delta f=140$. (c) $\Delta f=220$. (d) $\Delta f=280$. (e) $\Delta f=320$ Mc/sec.

experiments. As pointed out before, this caused a shift in the preferred directions of polarization and in the position of the polarization flip on the Doppler curve. Furthermore, from Fig. 8 we also see that a smaller slope of the rotation versus magnetic field curves results. From this we conclude that a greater anisotropy in the cavity Q has been introduced than was present in the original position of the reflectors (see Part I). It should be further mentioned that with the reflectors in this orientation some instability in the rotation was observed at lower power levels, resulting in erratic jumps, and hysteresis effects in the direction of polarization. Most of our experiments were performed with natural neon. Isotopically enriched Ne^{20}, however, was used in part of the experiments. Within our experimental accuracy no discernible differences were observed in the results with natural neon and isotopically enriched neon, with the possible exception of the power output versus cavity tuning curves.

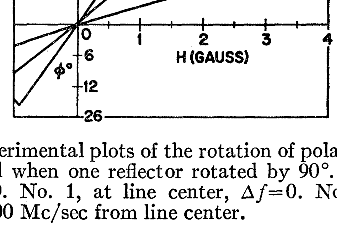


FIG. 8. Experimental plots of the rotation of polarization versus magnetic field when one reflector rotated by 90°. Relative laser intensity 10.0. No. 1, at line center, $\Delta f=0$. No. 2, $\Delta f=160$. No. 3, $\Delta f=300$ Mc/sec from line center.

Data similar to that displayed in Figs. 3 to 8 obtained with a recorder and by manually sweeping the magnetic field, may be obtained by applying a repetitive sawtooth waveform current to the solenoid and displaying the detector output on an oscilloscope. Figure 9 shows photographs of the oscilloscope display with such an arrangement taken at a high level of oscillation intensity; the bottom trace shows the solenoid current. The top photograph was taken with the resonance at the line center, the next ones at about 100, 200 and 300 Mc/sec removed from it. In all cases the oscilloscope sweep is 0.5 msec/cm and the sawtooth magnetic field scale is about 0.6 G/cm. Figure 9 shows a similar sequence taken at a lower power level to display the S-curve

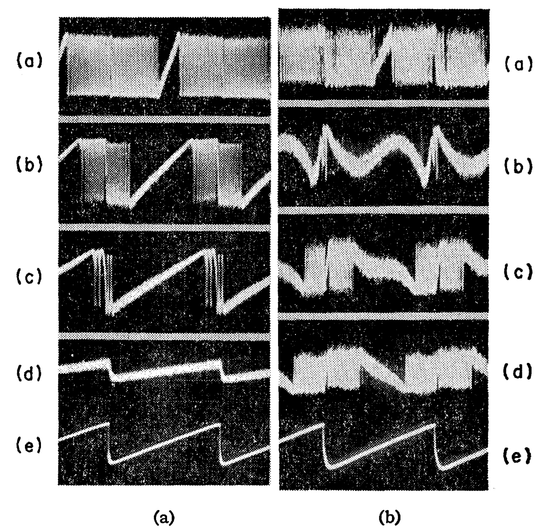


FIG. 9 (a) Oscilloscope displays of the rotation of polarization, linear region of the traces, with magnetic field. Analyzer at 45° to the polarization in zero magnetic field. Relatively high level of laser intensity. (a), $\Delta f=0$. (b), $\Delta f=100$. (c), $\Delta f=200$. (d), $\Delta f=300$. (e) Sawtooth waveform of the applied axial magnetic field, scale 0.6 cm^{-1}. Oscilloscope sweep 0.5 msec cm^{-1}. Note the circularly polarized beats either side of the coherence region. (b) Oscilloscope displays of the rotation of polarization with magnetic field. Analyzer at 45° to the polarization in zero magnetic field. Lower level of laser intensity. (a), $\Delta f=0$. (b), $\Delta f=70$. (c), $\Delta f=150$. (d), $\Delta f=250$. Note the occurrence of S-type curves in (b) and (c) before the change in sign of the slope occurs in (d). (e) Sawtooth waveform of the applied axial magnetic field, scale 6 G cm^{-1}. Oscilloscope sweep 0.5 msec cm^{-1}.

type dependence. The cavity resonance was set at the line center and then detuned by approximately 70, 150, and 250 Mc/sec as shown in the photographs from top to bottom. The oscilloscope sweep was 0.5 msec/cm and the magnetic field scale about 6 G/cm.

5. THE TRANSITION REGION

It is of some interest to study what happens in the transition region where the low frequency beats have appeared but before total circular polarization is observed (from 0.2 to 0.4 G in Fig. 3). When coherence is broken down and low-frequency beats first appear, the signal from the photomuliplier is not sinusoidal but shows a high harmonic content. Figure 10 shows such a signal displayed on an oscilloscope. The laser was operated at a fairly high-power level, the resonance tuned to line center, and the analyzer was in the direction of polarization in zero magnetic field. The oscilloscope sweep is 30 μsec/cm. The dc magnetic field is 0.18 to 0.27, 0.36, and 0.45 G from top to bottom. It is seen that at the lowest value of magnetic field an almost saw-tooth-shaped waveform is displayed. As the magnetic field is increased the waveform becomes more and more sinusoidal and the beat frequency between the oppositely circularly polarized oscillations increases.

In Fig. 10 (b) all conditions are the same as in Fig. 10(a) except the magnetic field is kept at 0.18 G and the analyzer is rotated. The orientation of the analyzer from the top to the bottom trace is at 0°, 45°, 90°, and 135°, respectively, with the direction of polarization in zero magnetic field. The explanation of the different waveforms obtained for the different orientations of the analyzer resides in the fact that while the amplitude of the beat frequency obtained when two oppositely circularly polarized waves are passed through an analyzer and detected by the photomultiplier is constant as the analyzer is rotated, the phase of the beat frequency does depend on the orientation of the analyzer. Thus, the harmonic components will combine differently for each analyzer orientation leading to the observed changes in the waveform. In support of this it was observed, by displaying the beat-frequency spectrum on a spectrum analyzer, that all beats were due to oscillations of opposite circular polarizations.

Figures 11(a) through 11(d) show some striking beat-frequency patterns as observed on the spectrum analyzer in this transition region. All beats arise from oppositely circularly polarized laser oscillations, as is readily verified by rotating the analyzer, and by removing it, in which case all such spectra disappear. The various figures refer to different positions of the cavity resonance within the Doppler linewidths, and the different traces within each figure are obtained as the magnetic field increases. It is seen that all figures have a number of harmonically related beat frequencies at the lower values of magnetic field, the number of which decreases as the fundamental beat frequency increases with increasing magnetic field. Such a phenomenon is observed

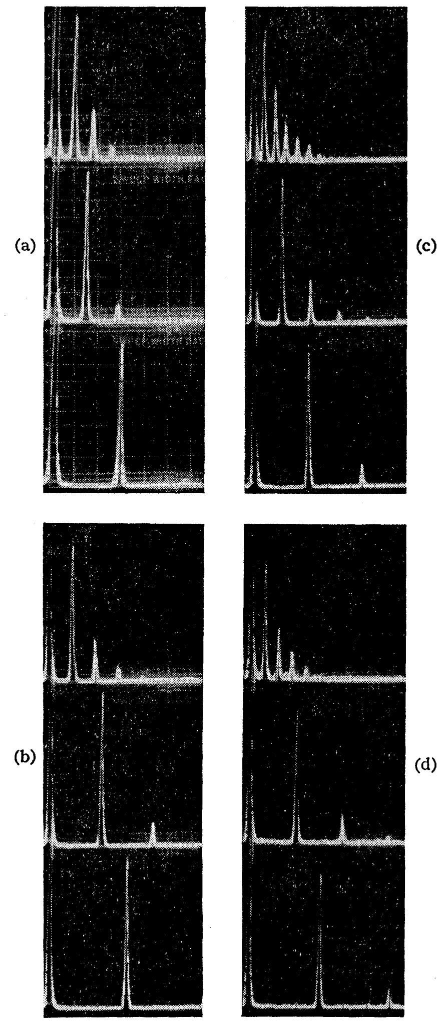


FIG. 11. Spectra of the beat frequency pattern in the transition region as detected by the analyzer-photomultiplier system. (a) Cavity tuned to line center, $\Delta f=0$. Spectrum analyzer sweep 10 kc/sec/cm. Magnetic field 0.11, 0.18, and 0.36 G from top to bottom. (b) $\Delta f=130$ Mc/sec. Spectrum analyzer sweep 20 kc/sec/cm. Magnetic field 0.54, 0.9, and 1.26 G. (c) $\Delta f=190$ Mc/sec. Spectrum analyzer sweep 20 kc/sec/cm. Magnetic field 0.36, 0.9, and 1.26 G. (d) $\Delta f=300$ Mc/sec. Spectrum analyzer sweep 20 kc/sec/cm. Magnetic field 0.45, 0.90, and 1.26 G. All components circularly polarized. Zero frequency on the left of all traces.

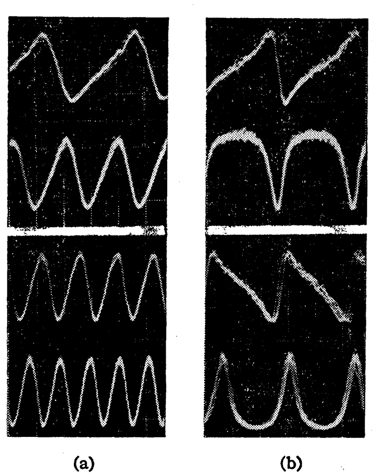


FIG. 10. Waveforms of the beat pattern in the transition region as detected by the analyzer-photomultiplier system. (a) Analyzer along direction of polarization in zero magnetic field. Relatively high power level. Variation of waveform with magnetic field. Magnetic field 0.18, 0.27, 0.36, and 0.45 G from top to bottom traces. (b) Variation of the waveform as analyzer is rotated with the magnetic field fixed at 0.18 G. Analyzer at 0°, 45°, 90°, and 135° with respect to the direction of polarization in zero magnetic field. Oscilloscope sweep 30 μsec cm^{-1}.

any time there is a transition from linear to circular polarization or vice versa, specifically, it is also present at the second coherence region at higher magnetic fields, to be described in the next section. The harmonic relations observed seem to indicate that some modulation phenomena occur in this intermediate region.

6. ADDITIONAL COHERENCE REGIONS

In accord with our previous observations on a short planar laser operating in a single mode, additional regions of coherence, or of mutual synchroniztion, between the oppositely circularly polarized oscillations occur at higher values of magnetic field. Figure 12 shows experimental curves of the beat frequency between such oscillations as a function of the magnetic field for two values of laser intensity, and for various positions of the cavity resonance within the Doppler linewidth. It is seen that after reaching a maximum, the beat frequency decreases to zero again at a higher value of magnetic field, and that there is a region of magnetic field around these points in which the beat frequency remains zero. These results are in general agreement with those derived from the theoretical consideration of beat frequencies,[2] with the additional result that these experiments show the range of magnetic field in the lock-in regions over which a mutual synchronization of the circularly polarized oscillations occurs. The polarization of the laser output is again linear and rotates as the magnetic field is varied within the zero-beat region. This is illustrated in Fig. 13, where the lower trace is the applied sawtooth magnetic field which is now increased to 8.7 G/cm so as to display the phenomena at higher values of magnetic field. The upper and middle traces, which are taken for slightly different positions around the line center, show the two regions, one near zero magnetic field and the other around 7 G or so, in which the polarization is linear and rotates. We see that the slopes of the ϕ-versus-H curves in each of these traces are of opposite signs in these two regions.

The existence of such additional coherence, or mutual synchronization, regions was indicated by the theoretical treatment of the beat frequencies and the rotation phenomena given previously.[2] The observed changes in the sign of the slope of ϕ-versus-H curves are accounted for by changes in the sign of the parameter a in such regions. Thus, after the initial coherence region near zero magnetic field, we have $4ac>b^2$, and circularly polarized beat phenomena appear, but eventually, due to the dispersive properties of the medium, a starts to decrease in magnitude toward zero and will change sign in the second coherence region. As a specific example, we consider the laser tuned to the line center. Then we find Eq. (41) of Part I, that for $\gamma_{ab}/2\pi=20$Mc/sec, $\eta_r\approx 1$, $\eta_y=1.2$, $a=0$ when the Zeeman shift $(\omega_r-\nu_n)/2\pi=25$ Mc/sec, and for $\eta_r\approx 1$, $\eta_y=2$, $a=0$ when H corresponds to frequency shift around 60 Mc/sec. The second coherence region will thus occur at a higher value of magnetic field for the higher value of laser intensity, and is in agreement with the results for Curves No. 1 and No. 4 of Fig. 12. For operation off the line center as in the other curves of Fig. 12, a simialr explanation holds, though it requires a more detailed knowledge of the dispersion functions involved, and variations in the decay constants γ_a and γ_b may also occur due to collision processes.

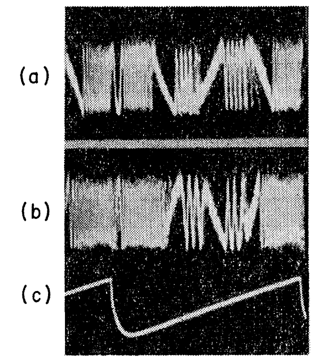


FIG. 13. Oscilloscope display of the second region of the type of coherence giving the rotation of polarization with magnetic field. Note that the slope of ϕ versus H in the second region changes sign in agreement with the theory. Curves (a) and (b) taken for slightly different positions around the line center. (c) Sawtooth waveform of the applied axial magnetic field, 8.7 G/cm. Oscilloscope sweep 0.35 m sec/cm.

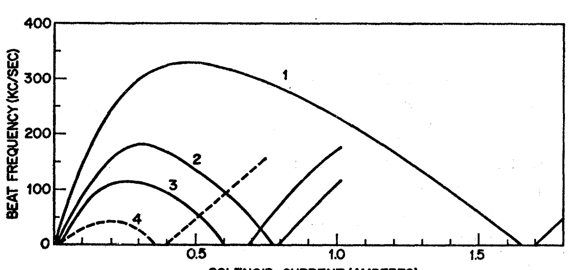


FIG. 12. Variation of the beat frequency between oppositely circularly polarized laser oscillations with magnetic field. Full curves—relative laser intensity 3. No. 1, $\Delta f=0$. No. 2, $\Delta f=100$ Mc/sec. No. 3, $\Delta f=300$ Mc/sec. No. 4, $\Delta f=0$, relative laser intensity 1. Note the second coherence region shown in all curves.

7. CONCLUSIONS

In zero magnetic field the output of the planar, or internal-optics, lasers used here is linearly polarized, with the direction of polarization determined by small anisotropies in the reflectors forming the resonator. When small axial magnetic fields are applied to such a laser the magnetic sublevels of the atomic states involved in the laser transition are slightly separated, but remain coherent over a finite range of magnetic field. In this region, the laser polarization remains linear but rotates with increasing magnetic field, until a rotation of about 45° has been attained. When the rotation nears 45°, the laser output gradually changes from linear polarization into two oppositely rotating circularly polarized waves, indicating that coherence between the magnetic sublevels then disappears. This may occur at quite low values of magnetic field, which at the higher oscillation intensities is as low as 0.1 G. As the magnetic field is increased further, the frequency difference between the two circularly polarized modes increases up to a maximum and then decreases to zero, at which point the polarization again becomes linear and a rotation is again observed. This second coherence region occurs at magnetic fields of 10 G or higher depending on conditions.

The experimental observations made here show that in accord with the theoretical predictions of Part I, the slope of the rotation versus magnetic field curves increases with increasing intensity of the laser oscillation, and decreases with the detuning of the cavity resonance from the center of the Doppler linewidth, with increasing total gas pressure, and with increasing anisotropy in the Q value of the cavity. It is of interest to note that in the absence of a magnetic field the linear polarization of the laser assumes one of two orthogonal preferred directions, and as the cavity resonance frequency is scanned over the Doppler linewidth at certain fixed points the polarization abruptly flips to the orthogonal direction. Some consideration of similar effects due to cavity anisotropies have been given by Lang and Bouwhuis,[6] and by Doyle and White.[7] It should also be noted that when the flipping point is close to the line center the slope of the rotation versus magnetic field curves is greatest at this point rather than at the line center.

This induced emission rotation phenomenon is quite interesting in that it is different from the observations with spontaneous emission processes as in the classical Hanle effect, where the 45° rotation is reached when the states have separated beyond their natural linewidth. Here the second coherence region shown in Figs. 12 and 13, on the other hand, occurs at sufficiently high values of magnetic field for which one may assume that the atomic transitions were not overlapping. This supports the view that the phenomenon is due to a mutual synchronization of the two oscillations in any region in which the beat frequency approaches zero. The transition region as exemplified by Figs. 10 and 11 is interesting and needs further investigation. Here the variation of the waveforms in Fig. 10 is due to phase changes between the beat frequencies as the analyzer is rotated. The appearance of a number of harmonically related beats in this transition region between the linear and circularly polarized oscillations, particularly at the lower values of magnetic field in Figs. 11(a)–11(d) is not so clear. However, they are presumably due to some intermediate time-dependent nonlinear coupling between the circularly polarized oscillations in this region of magnetic field.

ACKNOWLEDGMENT

We express our appreciation of the valuable efforts of L. B. Fowles on the construction of the short planar laser, and for instrumentation and assistance throughout the experiments.

[6] H. de Lang and G. Bouwhuis, Phys. Letters **9**, 237 (1964).
[7] W. M. Doyle and M. B. White, Appl. Phys. Letters **5**, 193 (1964).

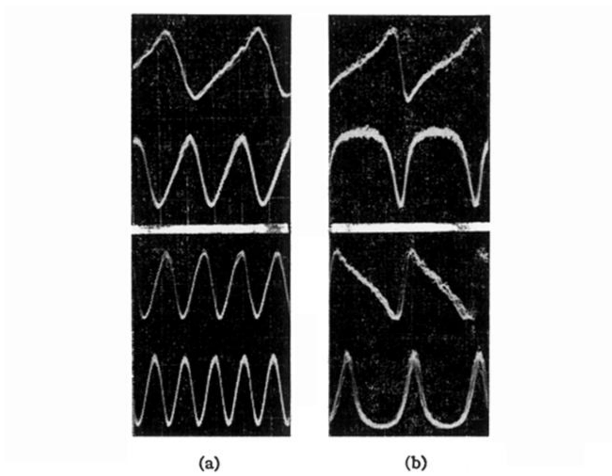
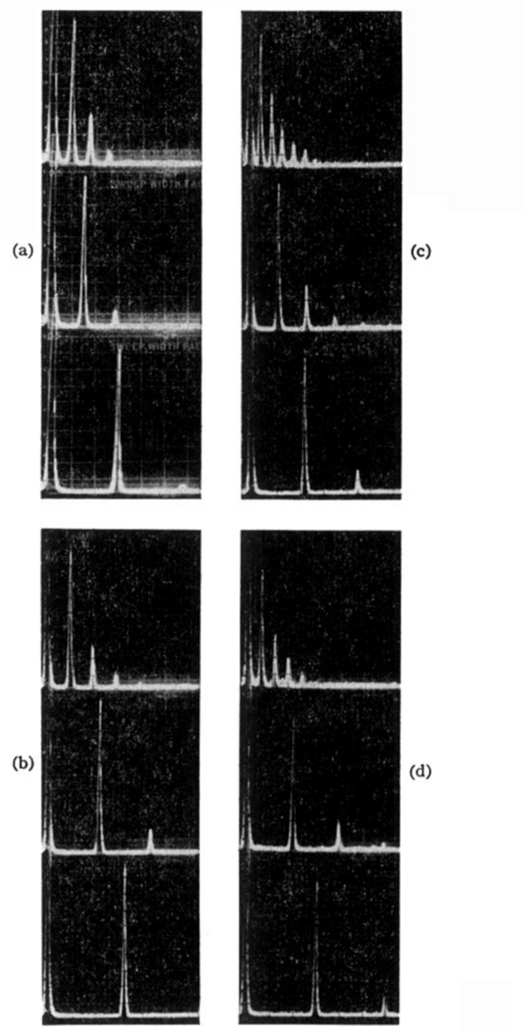


FIG. 10. Waveforms of the beat pattern in the transition region as detected by the analyzer-photomultiplier system. (a) Analyzer along direction of polarization in zero magnetic field. Relatively high power level. Variation of waveform with magnetic field. Magnetic field 0.18, 0.27, 0.36, and 0.45 G from top to bottom traces. (b) Variation of the waveform as analyzer is rotated with the magnetic field fixed at 0.18 G. Analyzer at 0°, 45°, 90°, and 135° with respect to the direction of polarization in zero magnetic field. Oscilloscope sweep 30 μsec cm^{-1}.



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(a)

(b)

(c)

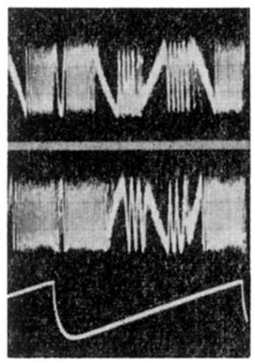
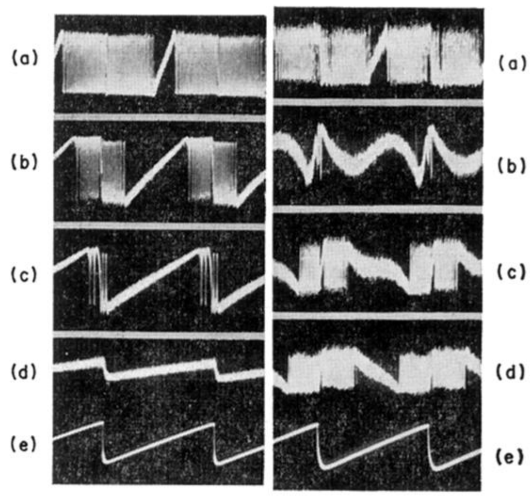


FIG. 13. Oscilloscope display of the second region of the type of coherence giving the rotation of polarization with magnetic field. Note that the slope of ϕ versus H in the second region changes sign in agreement with the theory. Curves (a) and (b) taken for slightly different positions around the line center. (c) Sawtooth waveform of the applied axial magnetic field, 8.7 G/cm. Oscilloscope sweep 0.35 m sec/cm.



(a) (b)

FIG. 9 (a) Oscilloscope displays of the rotation of polarization, linear region of the traces, with magnetic field. Analyzer at 45° to the polarization in zero magnetic field. Relatively high level of laser intensity. (a), $\Delta f=0$. (b), $\Delta f=100$. (c), $\Delta f=200$. (d), $\Delta f=300$. (e) Sawtooth waveform of the applied axial magnetic field, scale 0.6 cm^{-1}. Oscilloscope sweep 0.5 msec cm^{-1}. Note the circularly polarized beats either side of the coherence region. (b) Oscilloscope displays of the rotation of polarization with magnetic field. Analyzer at 45° to the polarization in zero magnetic field. Lower level of laser intensity. (a), $\Delta f=0$. (b), $\Delta f=70$. (c), $\Delta f=150$. (d), $\Delta f=250$. Note the occurrence of S-type curves in (b) and (c) before the change in sign of the slope occurs in (d). (e) Sawtooth waveform of the applied axial magnetic field, scale 6 G cm^{-1}. Oscilloscope sweep 0.5 msec cm^{-1}.