Table I. Photocurrent data.

	$I_e(+)$	$I_x(+)$	$I_e(-)$	$I_x(-)$
Light incident at A	1.17×10^{-5}	1.15×10^{-7}	4.13×10^{-6}	3.12×10^{-8}
Light incident at C	1.03×10^{-5}	2.46×10^{-6}	1.44×10^{-6}	7.21×10^{-7}

tered from the inner cylinder. This behavior was also confirmed for a range of coverages at B and the end of the tube.

As would be consistent with our interpretation, we could observe a tendency of $I_x(+)$ to vary independently from $I_e(+)$ by locally cooling the tube at A and varying the wall temperature at C within narrow limits. This test, however, is complicated by the difficulty of maintaining a desired temperature distribution and by variations in reflectivity, transmissivity, and photoelectric sensitivity with coverage. Again, $I_x(-)$ was too small to make statements about its behavior.

Before conducting the experiment described above, we attempted to study photoion emission by means of several systems that were so designed that only the region on the electrode illuminated by the direct light beam was cesium coated. We failed to observe any current that could be attributed to photoionized cesium.

We wish to thank G. Medicus and O. P. Breaux for generous discussion of their results.

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MODE-LOCKED LASER AND THE 180° PULSE

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We suggest that the pulses traveling back and forth in a mode-locked laser oscillator are 180° pulses and show that experimental measurements of the width of the pulse in a self-locked He-Ne laser as a function of intensity agree well with the calculated 180° pulse widths for the medium.

When a gas laser operates in a number of free-running longitudinal modes, their frequencies are pushed and pulled from the positions of the cavity resonances by the effects of competition and dispersion in the gain medium. The laser output power characteristically fluctuates in a random way. Under certain circumstances, it is possible to adjust the laser so that the output consists of a periodic train of pulses at the round-trip synchronous frequency ($c/2L$) of the resonator.[1-3] In this case, all of the oscillating modes occur exactly at the cavity resonances (i.e., all the beat frequencies are exact multiples of $c/2L$). To explain this, one could consider the frequency spectrum and attempt to account for the effects of competition in the nonlinear medium between all of the oscillating longitudinal modes (see, for example, Lamb[4]). This becomes exceedingly complex when more than a few modes are present. In general, the response of a nonlinear medium to a single frequency is not simply related to what will happen in the presence of several frequencies.

Another way of approaching the problem is to look for a simple model which will predict the transient response of the medium and then account for the observed behavior using time-domain analysis. We could adopt as a model a gyromagnetic spin system with a majority of magnetic moments antiparallel to an assumed magnetic field which produces a transition frequency of γH (where γ is the gyromagnetic ratio for the spins). In the presence of a stimulating optical field h in a plane normal to H, the spins are induced to precess about H and radiate their energy while dropping into alignment parallel with H. If the stimulating wave is a pulse of just the right duration, the spins will be flipped exactly 180°, and this constitutes what has been called a "180° pulse."[5] In this case, the maximum amount of energy is contributed to the pulse by the spin system.

We have asked the question, "Is it not possible that in a self-pulsing laser[6] the pulses traveling back and forth in the resonator have adjusted themselves in intensity and duration so that they are exactly 180° pulses?" If so, we should be able to use this picture to gain improved understanding of the physical processes involved.

Figure 1(a) illustrates the variation of the population difference between upper and lower laser levels immediately after applying an intense radiation field at the resonant frequency of a homogeneously broadened line. Figure 1(b) shows the power radiated by the medium. The justification for the form of these curves will be discussed later. If the field lasts longer than required for a spin flip (population inversion), it can be seen that the medium will amplify the first part of the pulse and attenuate the last part, hence distorting and shortening the pulse. Similarly, a pulse of less than 180° would be lengthened. A self-consistent pulse which is amplified without distortion must, therefore, have the intensity and duration product required for a 180° pulse. This result

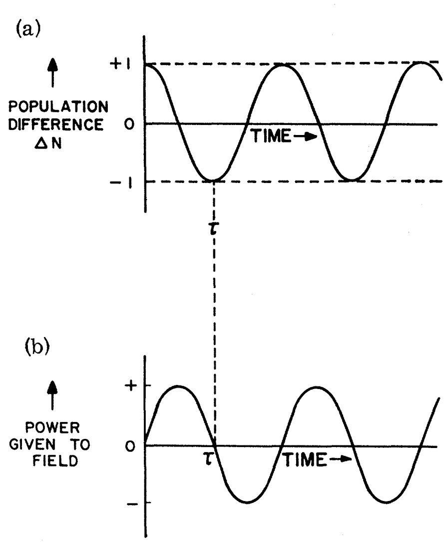

FIG. 1. (a) The normalized population difference ΔN as a function of time for $\omega = \omega_0$, and (b) the corresponding plot of the power given to the radiation field.

can also be derived in a more rigorous manner.

Wittke and Warter[7] and Arecchi and Bonifacio[8] have shown that in a traveling-wave laser amplifier, steady-state pulses of unique shape should result after an arbitrary input pulse has traveled a sufficient distance through the medium. In fact, for an amplifier with sufficiently low loss per unit length, they show that this steady-state pulse should approach a 180° pulse. Tang and Silverman[9] and Abella, Kurnit, and Hartmann[10] have discussed related problems.

Let us now calculate the "size" of a 180° pulse for the 6328-Å transition of a He-Ne laser. We will consider a two-level system with resonant frequency ω_0 and subject this to a perturbation $V\sin(\omega t)$, where $V = e\vec{E}_0 \cdot \vec{r}$. Here the incident field is assumed to be $\vec{E} = \vec{E}_0 \sin(\omega t)$ and $e\vec{r}$ is the dipole moment of transition. To simplify the calculations, we have assumed a constant intensity of perturbing field for the duration of the pulse. Calculations based on a more realistic pulse shape have been made, but the essential results are contained in this simple model. If ΔN is the (normalized) population difference between the upper and lower laser levels, and we assume $\Delta N = 1$ at $t = 0$, we can write, following Lamb,[11]

$$\Delta N = 1 - \frac{2|V|^2 \sin^2\{\tfrac{1}{2}t[(\omega-\omega_0)^2 + |V\hbar|^2]^{1/2}\}}{\hbar^2[(\omega-\omega_0)^2 + |V/\hbar|^2]} \qquad (1)$$

for t short compared with atomic pumping and decay times. Figure 1 shows a plot of Eq. (1) assuming $\omega = \omega_0$ and constant E_0. The power given to the incident radiation field is proportional to $d\Delta N/dt$ and is also plotted in Fig. 1. Note from Eq. (1) that a pulse of incident radiation of length

$$\tau = \pi[(\omega-\omega_0)^2 + |V/\hbar|^2]^{-1/2},$$

will cause the maximum change in the population difference. We shall call this a 180° pulse. If the laser resonance line is inhomogeneously broadened, each group of atoms will have a different ω_0, and the length of the effective 180° pulse will be some average over all groups of atoms. By determining $\vec{E}_0$ from the experimentally observed intensity, and $e\vec{r}$ from the observed spontaneous transition time for the laser levels,[12] an approximate value for a 180° pulse can be predicted.

Predicted pulse durations were compared with experimentally observed durations for a number of different pulse intensities. Mea-

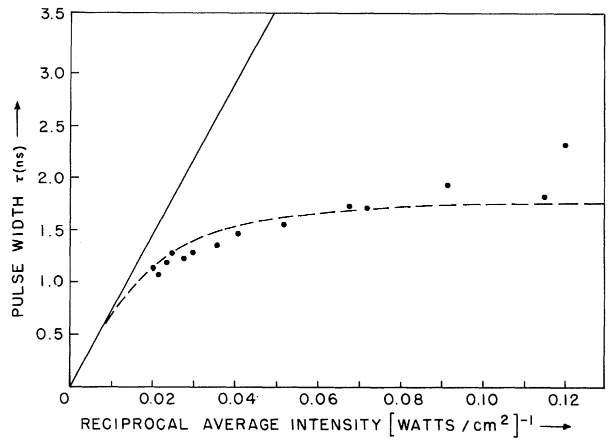

FIG. 2. Experimental[13] and theoretical plots of pulse widths as a function of reciprocal average intensity. The dots indicate the experimental measurements, the solid line is the computed pulse width assuming $\omega = \omega_0$, and the dashed curve is the computed pulse width assuming $|\omega - \omega_0|/2\pi = 275$ Mc/sec.

surements were made using a 30-cm, 4-mm-bore He-Ne laser tube operating at 6328 Å in a 250-cm cavity. Self-locked pulsing was observed with a 16.7-nsec periodicity when the laser tube was situated near the center of the cavity. The observed[13] and theoretical pulse widths have been plotted in Fig. 2 as functions of the reciprocal average output intensity. If the line were homogeneous with $\omega_0 = \omega$, $\tau = \pi/|V/\hbar|$ and the straight line should result.[14] In order to account for the fact that most of the atoms in the interaction are Doppler-shifted from their natural resonance frequency, we have assumed, for simplicity, that all atoms are removed by some average frequency separation from the frequency of the stimulating radiation. The best fit to the experimental points was obtained for $|\omega - \omega_0|_{\mathrm{Av}}/2\pi = 275$ Mc/sec. This seems a reasonable value for the frequency spectra observed.

A more detailed discussion of the theory and experiments will form the basis of a subsequent paper.

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[5]See, for example, E. C. Hahn, Phys. Rev. 80, 580 (1950).

[6]It seems quite possible that at least some of these considerations should also apply to lasers which are mode locked by internal-modulation techniques.

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[10]I. D. Abella, N. A. Kurnit, and S. R. Hartmann, Phys. Rev. 141, 391 (1966).

[11]W. E. Lamb, Jr., in Lectures in Theoretical Physics, edited by W. E. Brittin and B. W. Downs (Interscience Publishers, Inc., New York, 1960), pp. 435-483.

[12]The value of the spontaneous transition time used for this calculation was taken from P. W. Smith, J. Appl. Phys. 37, 2089 (1966), using the value which makes the calculated saturation parameter ω_0 agree with experiment.

[13]τ is the width of a rectangular pulse "equivalent" to the observed pulse. The observed pulses were assumed to be Gaussian and the rectangular pulses were required to have the same energy and the same integral of field intensity over time as the Gaussian pulse. τ is then 2.13 times the full width of the observed pulse at half-maximum intensity.

[14]Since for this condition the average intensity is proportional to τE_0^2 and $E_0 \sim 1/\tau$, the average intensity is proportional to $1/\tau$.