Time structure for a mode-locked argon laser

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Results are reported of an experimental study of the time structure of the radiation emitted by a mode-locked argon laser. The structure was examined directly with a photoelectric recorder FER2-1 (resolution limit 0.07 nsec). These experiments showed that, just above the generation threshold, the observed radiation pulses were satisfactorily described by the standard intensity formula obtained on the assumption that the initial phases of the generated oscillations were zero. This condition is not always satisfied when the generation threshold is substantially exceeded. A model is proposed to explain the observed structure of the emitted radiation.

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Despite the considerable number of published papers on the properties of continuously operating mode-locked gas lasers, the time structure of the radiation emitted by them has not been adequately investigated. Experiments are usually performed either with a view to developing mode-locking techniques[1] or to determine the different generation modes.[2-5] The time structure of the emitted radiation was analyzed theoretically in[6,7], and in the only experimental paper[8] the generation structure was investigated for a neon-helium laser, using a fast photodiode and a stroboscopic oscillograph.

In this paper, we report the first direct observation of the time structure of the radiation emitted by a mode-locked argon laser. We used the DArK-9.000 tube of a standard argon laser. The mode-locking state was determined by the operating conditions, namely, the discharge current, gas pressure, and resonator parameters. The time scan was carried out by the photoelectric recorder FÉR2-1 with a nominal resolution limit of 0.07 nsec.

The experiment showed that the mode-locking of longitudinal modes was relatively unstable because of the nonequidistance of the spectrum due to the pulling effect. Stable mode-locking well away from the generation threshold (relative excitation $\eta = k_0/k_l \sim 4$, k_0—unsaturated gain, k_l—level of losses) turned out to be possible when the generation region was restricted. The use of a three-mirror resonator for this purpose enabled us to obtain stable locking of three modes (Fig. 1b).

When, on the other hand, the laser resonator contained an absorbing cell,[1] it was possible to achieve mode-locking for several tens of longitudinal modes with $\eta \sim 12$. The generated pulse repetition frequency usually exceeded the frequency of intermode separation under these conditions. Pulses of length $\tau = 0.4$ nsec were produced in the experiments (Fig. 1c) with a repetition period of 6.1 nsec and peak power $P_p = 4$ W at mean generated power $P_{cont} = 0.26$ W.

A model was developed to describe this behavior. Figure 1d illustrates the mode-locking of transverse modes of the argon laser. The observed transverse scanning frequency was about 1400 MHz. Details of the experiments are given below.

1. Generation in three longitudinal modes ($\lambda = 5145$ Å) was produced with a resonator incorporating a passive spherical mirror and two flat mirrors ($r_1 = 0.8$, $r_2 = 0.13$) forming an additional short-gap Fabry-Perot interferometer. For a total resonator length L = 210 cm ($c/2L \approx 71$ MHz), the optical distance between the flat mirrors was $l = 2.5$ cm ($c/2l \approx 6300$ MHz). The frequency interval between the modes in the generation spectrum was f = 430 ± 1 MHz. The mode structure was controlled by a scanning Fabry-Perot interferometer with a theoretical resolution limit of 13 MHz and dispersion band of 2060 MHz. The establishment of mode-locking was determined by examining the spectrum of intermode beats, using a photomultiplier and the S4-9 spectral analyzer.

Figure 1b shows the time scan of the generated radiation under mode-locking conditions. The time interval between the pulses is $T \equiv 1/f = 2.3$ nsec. This has enabled us to calibrate the nonlinear scan of the FÉR2-1 recorder and to determine the scan length. The full width at half-height of the generated pulse was found to be $\tau = 0.7 \pm 0.15$ nsec.

The temporal characteristics of the generated radiation were calculated from the formula

$$I(t)=\left[\sum_m E_m\cos(mft)\right]^2+\left[\sum_m E_m\sin(mft)\right]^2, \qquad (1)$$

where E_m is the m-th mode field amplitude, measured

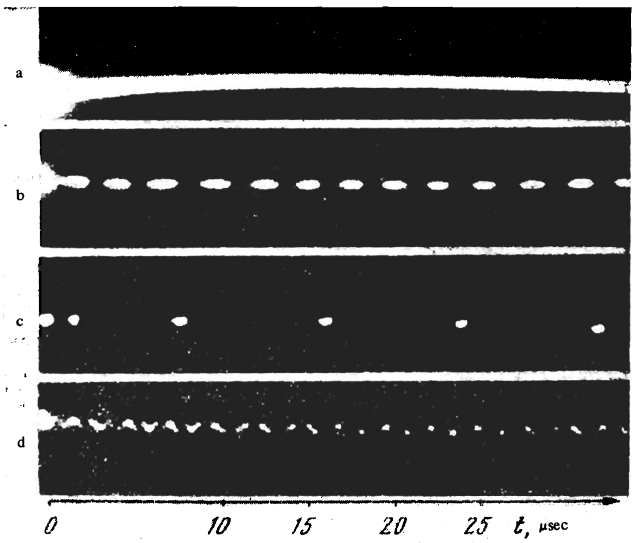

FIG. 1. Time scan of radiation from the argon laser: a—free generation, b—locking of three longitudinal modes in a laser with a three-mirror resonator, c—longitudinal mode-locking in a laser incorporating an absorbing cell in the resonator, d—transverse mode-locking-radiation scanning.

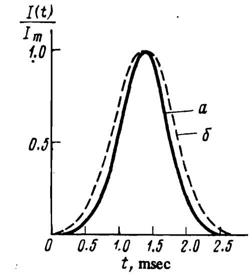

FIG. 2

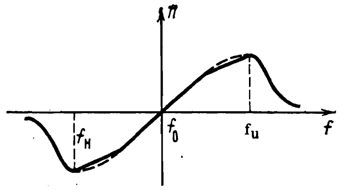

FIG. 3

FIG. 2. Experimental (a) and calculated (b) shapes of the radiation pulse from an argon laser using mode-locking of three longitudinal modes. The half-width of the generated pulse is 0.71 nsec. The theoretical half-width of the pulse is 0.97 nsec. Experimental uncertainty is about 20% and the time along the abscissa axis is in nanoseconds.

FIG. 3. Mode pulling corrected for gain saturation as a function of frequency (dispersion curve). n—Refractive index, f_0—central transition frequency, $\Delta f_g = f_u - f_L$—laser generation region, f_u and f_L—upper and lower frequencies (the solid curve illustrates the proposed subdivision of the dispersion curve into linear segments).

with the scanning Fabry-Perot interferometer. This expression was obtained in[8] on the assumption that the initial phases of the generated modes were zero. It is clear from Fig. 2 that calculations based on (1) yield good agreement with experiment.

2. In the experiments on generation structure, we used a two-mirror resonator of length L = 275 cm (frequency separation of modes $f^0 = c/2L = 54.8 \pm 1$ MHz). The resonator contained an absorbing cell. The width of the generation region at $\lambda = 4880$ Å in the absence of mode-locking was $\Delta f_g' \approx 4700$ MHz and, in the case of longitudinal mode-locking, $\Delta f_g'' \approx 6000$ MHz. This laser could therefore generate about one hundred longitudinal modes.

The time scan of the radiation emitted in the case of longitudinal mode locking showed that the pulse repetition frequency usually exceeded f^0. In our experiments, it was found that $f \equiv 3f^0 = 164.4$ MHz. A similar situation was observed earlier in[4] (in the case of the mode-locked neon-helium laser, the pulse repetition frequency exceeded by a factor of two the frequency of intermode separation). However, no explanation was offered for this phenomenon.

As already noted, we assumed that the initial phases of the summed oscillations, φ_m, were zero. However, in practice, this assumption is not, in general, valid. Analysis of the mode-locking process reported by Lamb[10] shows that the relative phase angle ψ should be time-independent during the mode-locking process. This leads to the following condition for the initial phases of the generated oscillations:

$$\varphi_m-\varphi_{m-1}=\varphi_{m+1}-\varphi_m+\text{const.} \tag{2}$$

When $\psi = 0$, the constant in (2) is also zero. Physically, this means that there is phase locking of equidistant or almost equidistant modes. If, on the other hand, dispersion in the active medium leads to an appreciable departure from the equi-distant distribution of modes in the spectrum, then, under the conditions of phase locking we have $\psi \neq 0$, and the constant in (2) should also be nonzero. It appears that the generation region can be divided into a number of segments, in each of which mode pulling can be regarded as linear. The initial phases of the oscillations in neighboring modes are then shifted by a constant amount in these segments, and change discontinuously between the segments.

This mode pulling effect is illustrated in Fig. 3 for three linear segments ($\kappa = 3$). When the initial phases of neighboring oscillations differ by $2\pi/\kappa$, this leads to a shift in time of the periodic sequence of pulses by the amount T/κ. The time structure of the generated radiation is then a periodic sequence of pulses, which is a superposition of three sequences. Within each sequence, the pulse repetition frequency is 54.8 MHz and the pulse length is $\tau = 3/\Delta f_g$. Each of the sequences is shifted relative to the other by one-third of the period $T \equiv 1/f^0$, and this leads to the repetition frequency $f = 3f^0$.

Under these conditions, the ratio of the peak power to the mean power should be equal to the number of modes in each group, N_{gr}, divided by the number of groups

$$N\approx\kappa^2 P_p/P_{cont} \tag{3}$$

where $N \approx \kappa N_{gr}$ is the total number of generated modes.

Our experiments thus show that the continuously-operating mode-locked argon laser can ensure high repetition and scanning frequency of radiation pulses. The fact that the shape of the light pulses in the case of mode-locking of equidistant modes is satisfactorily described by (1) can be used in the interpretation of data obtained with fast radiation detectors.

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[1] The absorbing cell [9] is a short discharge tube, filled with argon. It absorbs radiation at the generation wavelength. The purpose of the cell is to modulate the radiation by transmission and to give rise to partial restoration of the equidistance of modes.

[1] P. W. Smith, Proc. IEEE 58, 1342 (1970).

[2] T. Uchida and A. Ueki, IEEE J. Quantum Electron. QE-3, 17 (1967).

[3] P. W. Smith, IEEE J. Quantum Electron. QE-3, 627 (1967).

[4] F. R. Nash, IEEE J. Quantum Electron. QE-3, 189 (1967).

[5] J. M. Yarborough and J. L. Hobart, Appl. Phys. Lett. 13, 305 (1968).

[6] A. A. Grütter, R. Dändiker, and H. P. Weber, Z. Angew. Math. and Phys. 20, 574 (1969).

[7] R. Dändiker, H. P. Weber, and A. A. Grütter, ibid. 20, 572 (1969).

[8] P. W. Smith, Opt. Commun. 2, 292 (1970).

[9] M. S. Borisova, Opt. Spektrosk. 33, 1134 (1972) [Opt. Spectrosc. 33, 620 (1972)].

[10] W. E. Lamb, Phys. Rev. 134, A1429 (1964).

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56