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Operation Characteristics of a Cryptocyanine Mode-Locked Ruby Laser

Results of a detailed study of the operation characteristics of a cryptocyanine mode-locked ruby laser are given. The Brewster-angled ruby rod as well as the cryptocyanine cell were placed in different positions within the laser cavity. Trains of single spikes appearing at a time interval equal to the round trip time of the light in the cavity, as well as doubled, tripled and more complicated spike structures were observed, depending on the position of the cryptocyanine cell. Nearly full mode-locking was obtained when the cell was placed next to one of the resonator mirrors. On the other hand, mode-locking was very weak if the cell was shifted towards the center of the cavity.

1. Introduction

Mode-locking of laser emission is usually performed for a Neodymium-glass laser. The line-width of its emission is very broad (several tens of Å) and contains about 10^4 different longitudinal modes for a resonator length of the order of 1 m. Thus, the mode-locking process could be very effective. On the other hand, there are but very few experiments concerning mode-locking of ruby laser (see e.g., MACK [1], MOCKER *et al.* [2], MALYSHEV *et al.* [3], and SCHMAKPFEFFER and WEBER [4]). The line width is much narrower in this case (of the order of 0.1 Å) and, as a result, the number of oscillating longitudinal modes is relatively low. The present paper presents a detailed analysis of a cryptocyanine mode-locked ruby laser. The ruby as well as the cryptocyanine cell were placed in different positions within the resonator. Long (210 cm) and short (117 cm) resonators were used. The emitted pulse trains were detected by means of a fast high current photocell and displayed on the screen of a I 2–7 nanosecond type oscilloscope (made in USSR).

The origin of a short pulse emission by passively switched lasers was studied theoretically by FLECK [5], STATZ, TANG, DEMARS and BASS [6, 7, 8]. According to Fleck's results, single spikes appear in the train only in the case when the passive bleacheable absorber is placed next to one of the resonator mirrors. The passive absorber must have a sufficiently short lifetime of its upper excited level. Now suppose the absorber cell is placed 1 cm from the mirror. The round trip time for the light to travel twice the way between the mirror and the absorber is 68 ps, i.e. is comparable to the life-time of the upper absorbing level of the passive cell. The returning pulse finds the absorber still in a partially bleacheable state. Saturation of the absorber, according to Fleck's theory, requires several tens or even several hundred ns and a well determined spike structure in the train appears after many round trips of the light within the resonator. The incident and reflected (from the mirror) beams can overlap in the absorber, thus giving rise to generation of double, triple or even more complicated spike structures in the train.

In the course of our experiments, numerous observed laser trains could be interpreted on the basis of Fleck's theory. This was especially true in the case of a long resonator. If the resonator was shortened to about 1 m, mode-locking disappeared almost completely if the cryptocyanine cell was placed near the cavity center. In a short resonator the number of simultaneously oscillating longitudinal modes is probably too small to give an effective mode-locking process. All experimental data here presented were obtained with a laser working slightly above the thereshold. Concentration of the cryptocyanine in methyl alcohol was experimentally determined to give at this pumping level only a single giant pulse. Its transmission measured at the laser wave-length was 27%. The liquid cell containing cryptocyanine solution had a thickness of 6 mm. The Brewster-angled ruby rod (Swiss production, Hrand Djevahirdijan,

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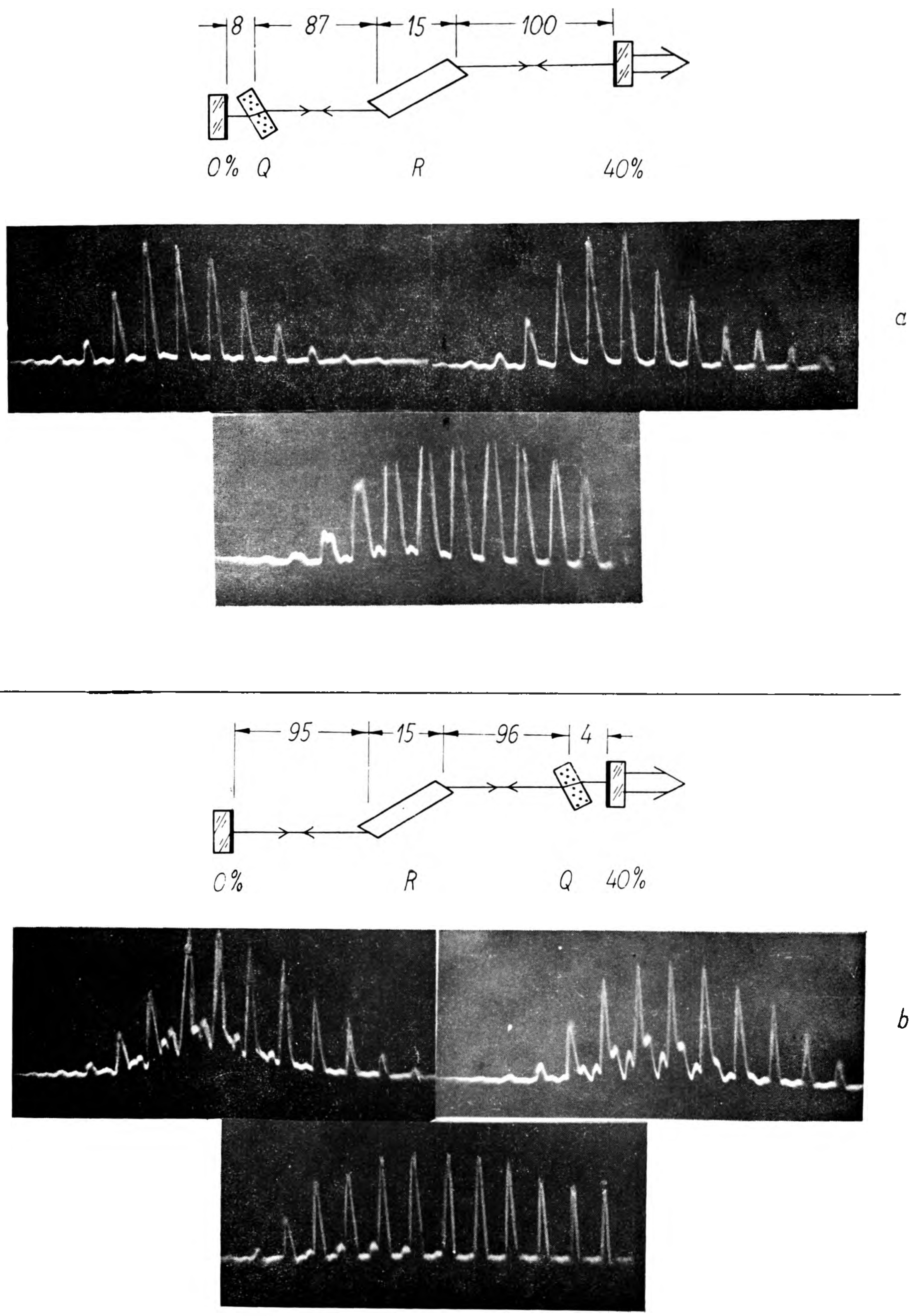


Fig. 1. Oscillograms of pulse trains emitted from ruby laser (long symmetric resonator). Q — cryptocyanine cell, R — ruby rod. Time base — 250 ns (full scale)

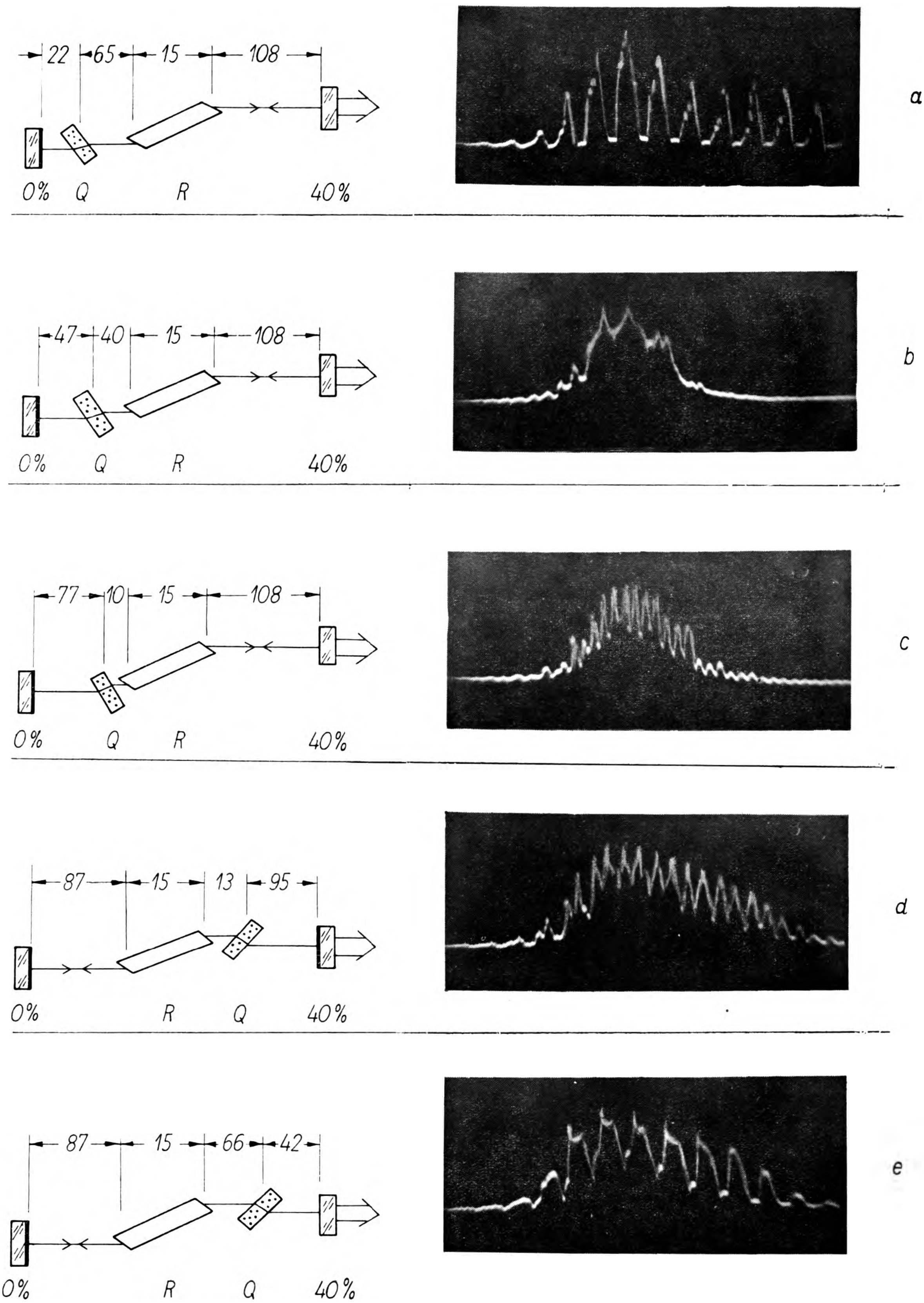


Fig. 2. Oscillograms of pulse trains emitted from ruby laser (long symmetric resonator)

$l = 150$ mm, $d = 7$ mm) was of 90° orientation. Its optical quality was extremely high. The laser was pumped by means of a helical quartz flash-tube. A forced system of water cooling of the ruby rod and of the flash-tube was applied.

Position of the cryptocyanine cell within the laser resonator will be denoted by z' (with respect to the 40% transmission mirror) or by z (in the case of the "0" mirror).

2. Experimental Results

I. RUBY ROD PLACED APPROXIMATELY IN THE CENTER OF THE LASER CAVITY. RESONATOR LENGTH — $L = 210$ cm

I. 1. Cryptocyanine cell placed next to the "0" transmission mirror (Fig. 1a)

The round trip time of the light within this resonator was about 14 ns. Fig. 1a shows several oscillograms of pulse trains obtained under identical conditions, with cryptocyanine cell placed very close to the "0" transmission mirror. Fluctuations in the output power are well known for almost all ruby lasers. The number of excited modes and the time and space patterns of the output beams change from pulse to pulse (see, e.g., the paper of ANDREYEV *et al.* [9]). Thus, mode-locking of ruby laser emission seems to be a rather troublesome problem. The spikes within the train appear after every 14 ns time interval, which is equal to the light round trip time in the resonator used. Sometimes, in the early part of the train, a small fine structures can be seen. The time interval between successive spikes is about 6 ns. This fine structure disappears after several tens of ns and in most cases can be interpreted as a transient phenomenon. The total duration of the laser emission ranged from 165 to 180 ns.

I. 2. Cryptocyanine cell placed next to the output mirror (Fig. 1b)

In comparison to the oscillograms of Fig. 1a, larger fluctuations in the output power in time were observed. Fig. 1b presents three oscillograms, obtained in identical conditions. Behind the strong main spikes appearing in the train after every 14 ns, two small spikes in the early part of the train are clearly visible. The last part of the train presents a well determined single spike structure. The total duration of the emission was about 180 ns. The time interval between two small successive spikes was 6 ns, i.e. similar to that observed in Fig. 1a.

I. 3. Cryptocyanine cell placed in various positions within the resonator (Fig. 2)

The degree of mode-locking is not so high as it was for the resonator arrangement shown in Fig. 1. The pulse train exhibits a complicated fine structure, especially when the cryptocyanine cell is placed close to the ruby rod, i.e. approximately at one third of the resonator length (Figs. 2c and d). Oscillograms 2b and c indicate also a strong pulse shortening to some 100–110 ns (total duration). The measured halfwidth of this pulse was only 30–35 ns. Accurate observations of the oscillograms (on film) show a triple fine structure. As the cryptocyanine cell was moved to the right with respect to the ruby rod (Fig. 2d and e), the pulse duration increased (in some experiments up to 200 ns) but the train structure remained complicated. Two main spikes with a small fine structure were generated.

II. NONSYMMETRIC RESONATOR. $L = 210$ cm

II. 1. Ruby rod placed in the vicinity of the output mirror (Fig. 3)

If the cryptocyanine cell is placed close to the "0" transmission mirror, good mode-locking conditions can be achieved. In the early part of the train, small frequency doubling effect was observed (Fig. 3a). Total duration of the laser emission was 180 ns. When the cryptocyanine cell was shifted to the position next to the output mirror (Fig. 3b), the emitted train was almost unchanged. After several tens of ns the frequency doubling effect disappeared and the train consisted of single spikes generated at a time interval of 14 ns (round trip time of the light within the cavity).

II. 2. Ruby rod placed in the vicinity of the "0" transmission mirror (Fig. 4)

The cryptocyanine cell was placed next to the "0" transmission mirror (Fig. 4a) or output mirror (Fig. 4b). In the first oscillogram of Fig. 4a, two distinct spikes instead of a single one were observed. Almost all of the other oscillograms taken in identical operation régime of the laser failed to exhibit such a highly developed double structure. Mode-locking seems to be complete, especially when the cryptocyanine cell is placed next to the output mirror (Fig. 4b).

The laser emission presented in Fig. 4 was 150-160 ns in duration; the first small spike appears

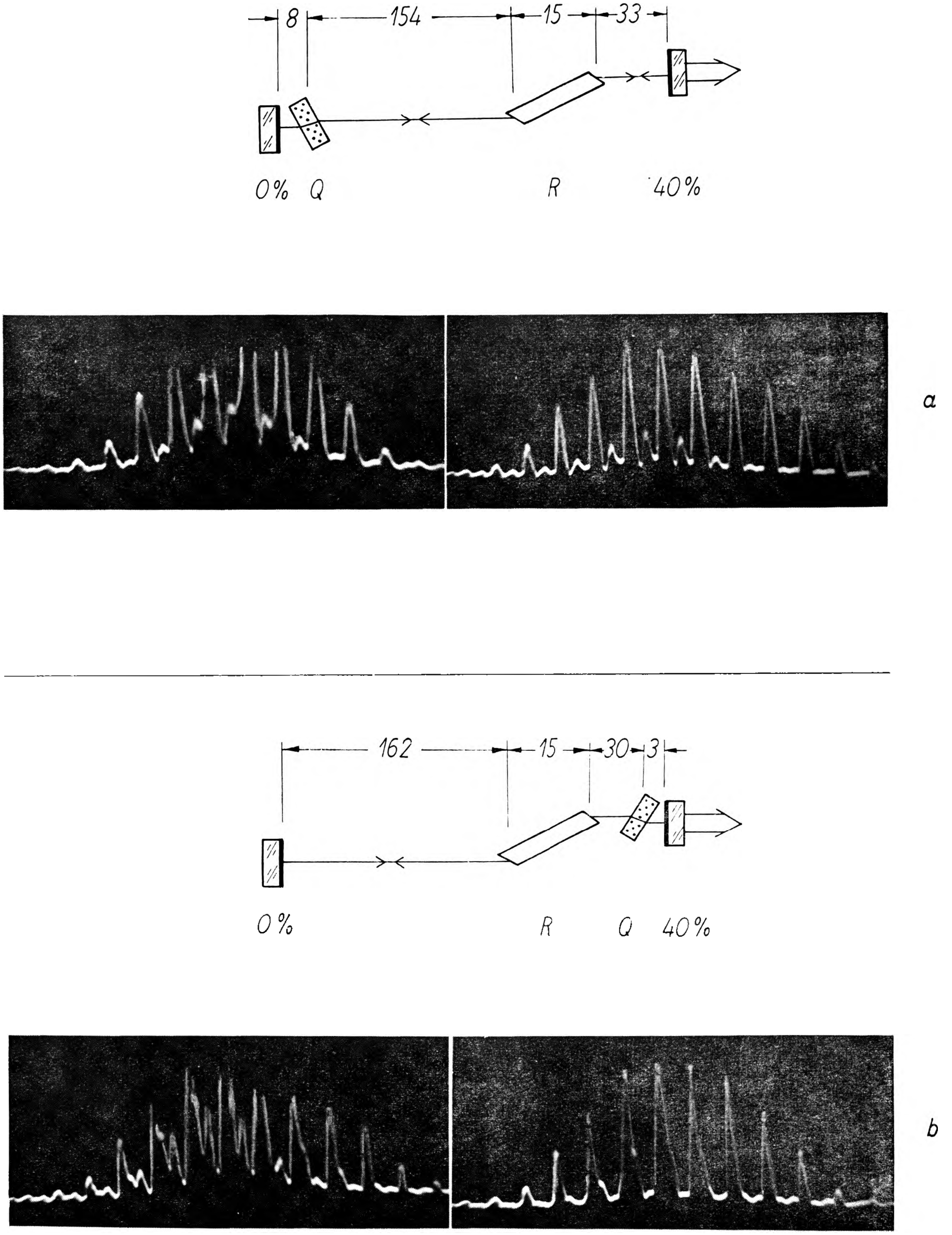
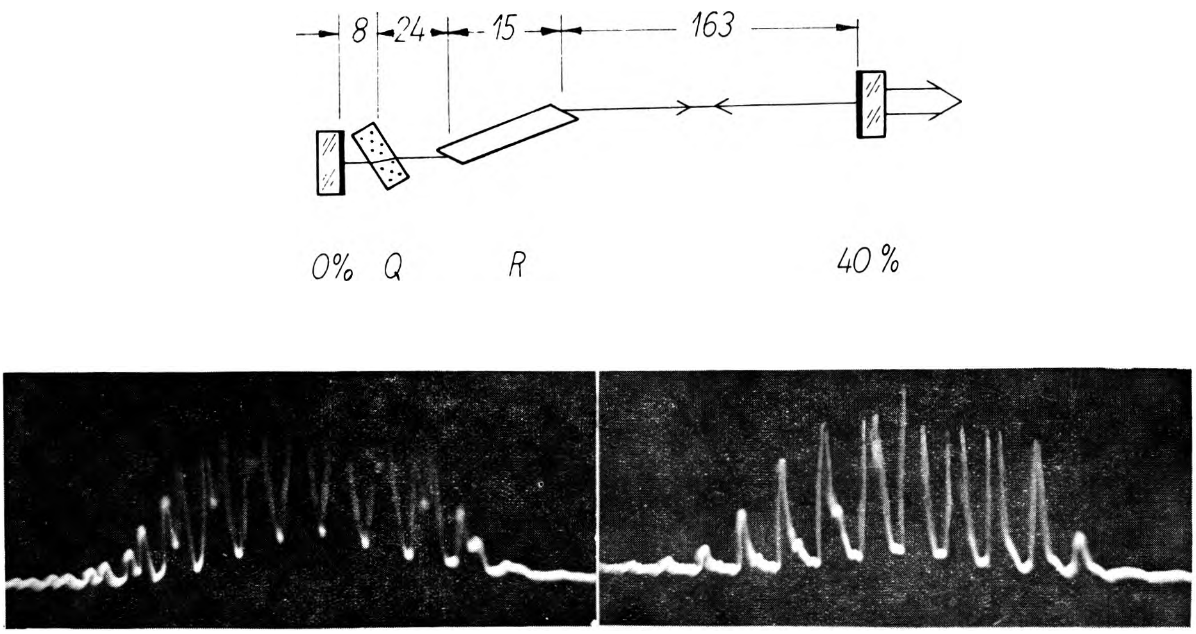
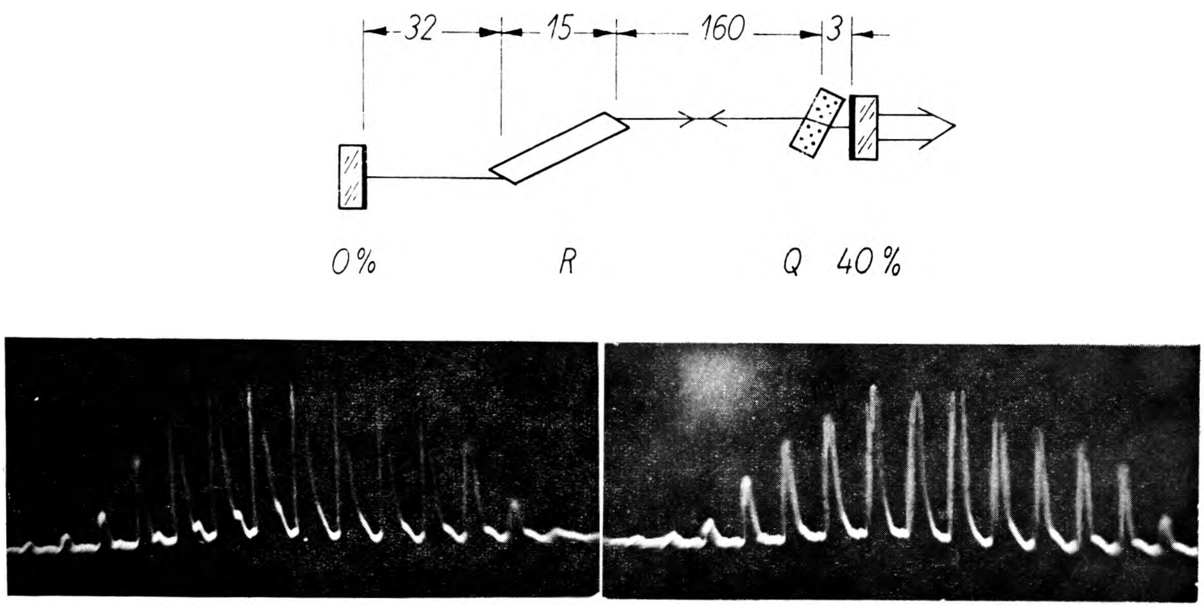


Fig. 3. Oscillograms of pulse trains emitted from ruby laser (long nonsymmetric resonator)



a



b

Fig. 4. Oscillograms of pulse trains emitted from ruby laser (long nonsymmetric resonator)

about 5 ns before the main spike, while the left side round trip time of the light (measured from the center of the ruby rod to the "0" transmission mirror) is only 3 ns.

Position of the ruby rod within the optical cavity of the laser practically did not disturb the emission train when the cryptocyanine cell was placed next to one of the resonator mirrors. Mode-locking was almost complete, frequency doubling or generating of more small spikes disappeared after several tens of ns, and the train presented a "pure" single spike structure. The time interval between successive spikes was equal to the light round trip time within the cavity.

III. NONSYMMETRIC RESONATOR. $L = 210$ cm. CRYPTOCYANINE CELL PLACED IN VARIOUS POSITIONS WITHIN THE LASER CAVITY

III. 1. Ruby rod placed in the vicinity of the outputs mirror (Fig. 5a, b and c)

The cryptocyanine cell was placed in various positions but not close to any of the resonator mirrors. Denote the distance between the mirror and the cell by z'. For $z' = 24$ cm, good mode-locking can be seen, the spikes being very little disturbed. The measured total duration of the pulse was 180 ns. For $z = 151$ cm (with respect to the "0" mirror) the pulse was shortened to about 120 ns, and three equally spaced spikes within the time interval of $\frac{L}{2c}$ were generated. The cell was approximately at a distance of $\frac{L}{3}$ with respect to the mirror in this case. For $z = 81$ cm, again poor mode-locking was observed, the total pulse duration remaining unchanged (about 120 ns). A triple spike structure can be seen.

III. 2. Ruby rod placed in the vicinity of the "0" transmission mirror (Fig. 5d, e, f)

For $z' = 30$ cm, the total pulse duration varied from 130 to 140 ns, and small spikes were generated at the main spike envelope. For $z' = 155$ cm, total pulse duration remained unchanged (about 130 ns) and the time interval between the small and the main spike was 4 ns. For $z = 19$ cm (the last oscillogram in Fig. 5), the total duration of laser emission varied from 120 to 140 ns, mode-locking was more evident and the substructure tended to disappear at the end of the train.

IV. SHORT SYMMETRIC RESONATOR. $L = 117$ cm

Cryptocyanine cell placed in various positions within the laser cavity (Fig. 6).

In the series of experiments here described the ruby rod was placed approximately in the center of the cavity. Fig. 6 presents oscillograms of pulse trains obtained for this resonator arrangement. Good mode-locking, seen in oscillograms 6a and 6d, was obtained when the cryptocyanine cell was placed very close to one of the resonator mirrors. The spikes appear at an 8 ns time interval, which is equal to the light round trip time in the resonator. The total emission seen in Fig. 6a exceeded 200 ns, and decreases to 140 ns in oscillogram 6d. When the cryptocyanine cell was placed near the center of the cavity (Figs. 6c and 6b), mode-locking practically disappeared and the emission became very irregular. The total duration of the pulse decreased to 120–130 ns (in Fig. 6b) or 100 ns (as in Fig. 6c).

In comparison to the case of the long resonator ($L = 210$ cm), displacement of the cryptocyanine cell within the cavity appears as more critical and almost no mode-locked operation can be achieved if the cell is placed apart from the mirrors.

V. CONCLUSIONS

Markin [10] calculated the influence of position of the absorbing cell on the mode-locking process assuming that all of the generated modes are equal in intensity. It is then possible to find a set of phase relations between these modes which yield the lowest absorption of energy in the passive absorption cell (e.g. cryptocyanine in solution). Let us assume that the cell is placed in a determined position z with respect to the mirror. The Markin minimum loss analysis gives the following phase relations:

For $\frac{L}{z} = 0$ (cell placed very close to the resonator mirror)

$$\varphi_{m+1} - \varphi_m = \varphi_m - \varphi_{m-1} + 2k\pi.$$

For $\frac{z}{L} = \frac{1}{2}$ (cell placed in cavity center)

$$\varphi_{m+1} - \varphi_m = \varphi_m - \varphi_{m-1} + (2k+1)\pi.$$

For $\frac{z}{L} = \frac{1}{3}$

$$\varphi_{m+3} - \varphi_m = \varphi_{l+3} - \varphi_l = 2k\pi.$$

Above, m and l denote mode indexes, and k is an integer. For $\frac{z}{L} = 0$, all components of equal frequencies have also equal phases. For $\frac{z}{L} = \frac{1}{2}$, all even components have the same phases, but among the odd components some have phases opposite to the others.

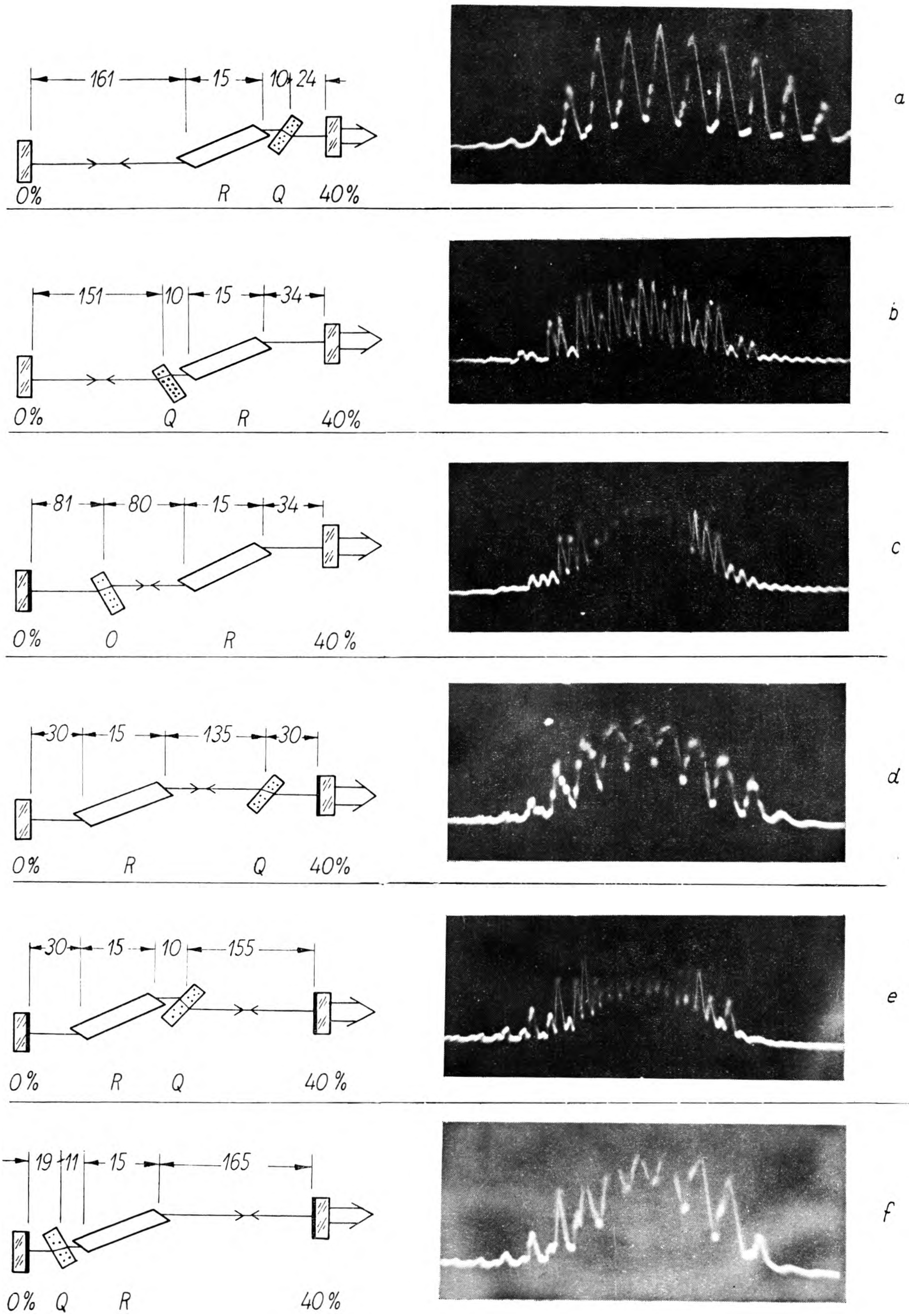


Fig. 5. Oscillograms of pulse trains emitted from ruby laser (long nonsymmetric resonator)

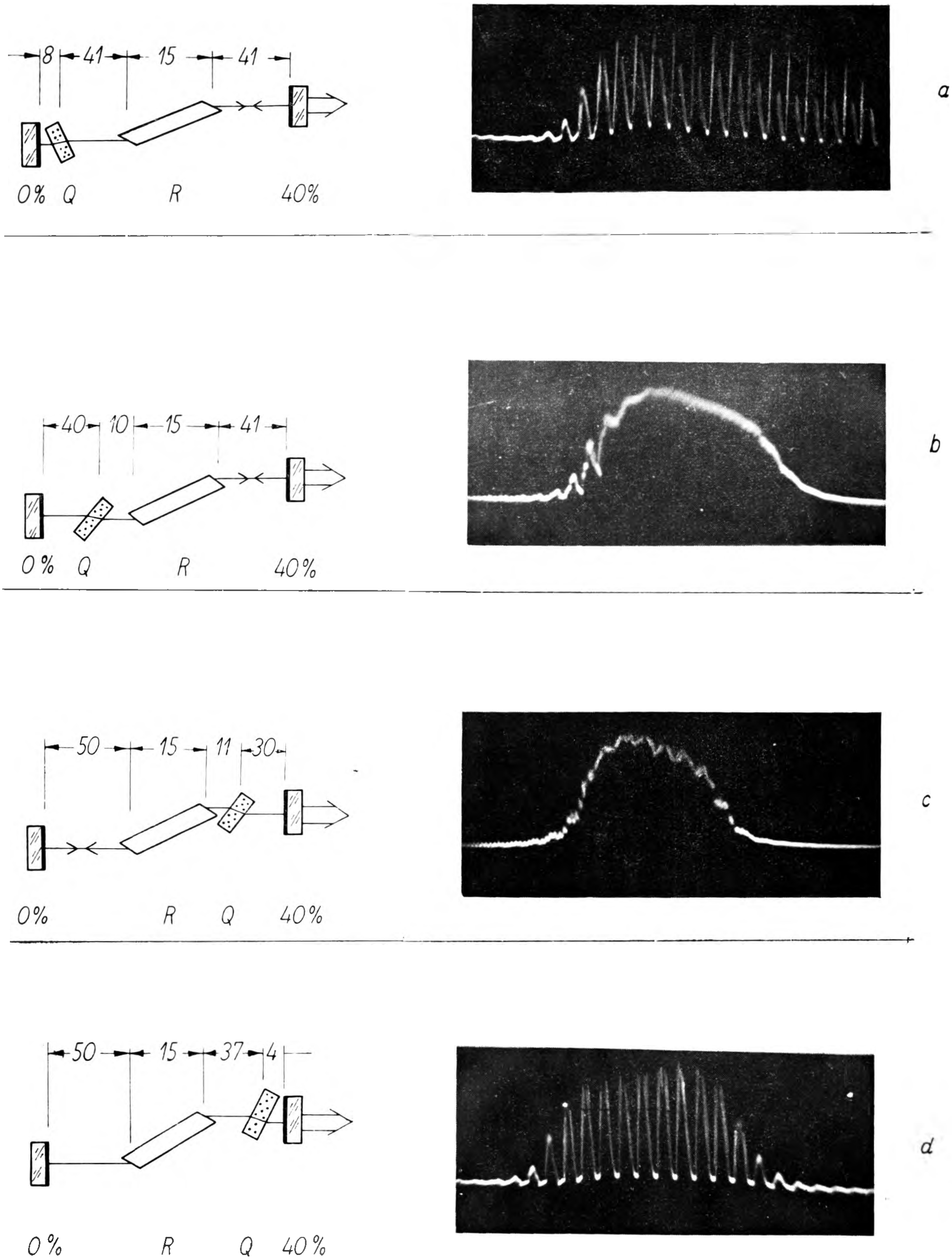


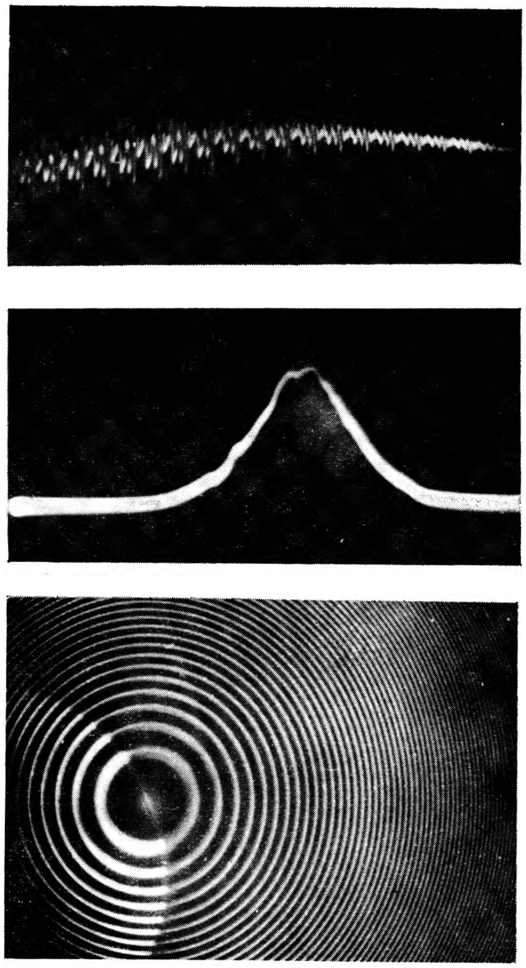
Fig. 6. Oscillograms of pulse trains emitted from ruby laser (short symmetric resonator)

The output signal contains single spikes (for $\frac{z}{L} = 0$), double spikes (for $\frac{z}{L} = \frac{1}{2}$), and a triplet array (for $\frac{z}{L} = \frac{1}{3}$). From Markin analysis as well as from those of FLECK [5] or HARRACH and KACHEN [11] it does not follow that the degree of mode-locking depends on the position of the passive cell within the cavity. Changing the cell position causes merely variations in the multiplicity of spikes appearing in the output signal. However, from the experimental results described here, mode-locking is found to depend on the position of the cell and moreover the pulse duration decreases when the cryptocyanine cell is shifted towards the center of the cavity. It should be pointed out that SACCHI *et al.* [12] suggested that mode-locking tends to disappear for $\frac{z}{L} = \frac{1}{3}$. It is thus reasonable to assume that strong mode-locking associated with effective energy exchange between different modes sustains the laser action for a longer time.

VI. SELF-MODE-LOCKING

With the Brewster-angled ruby rod and no bleacheable absorber present in the cavity, strong self-mode-locking was observed. A typical display of the emission characteristics is shown in Fig. 7a. The time interval between the main successive spikes is equal to the light round trip time in the cavity. The emission time-characteristics were not the same at successive laser shots. Behind the main spikes appearing at a time interval of $\frac{2L}{c}$, two or three smaller spikes were generated. On the other hand, a similar ruby rod having flat terminals perpendicular to the rod axis did not exhibit any self-mode-locking. Also, bleacheable absorber added to this resonator did not enchance the effect of mode-locking, as seen in Fig. 7b, which shows a typical giant pulse (measured halfwidth of the pulse in 30 ns). The last picture in Fig. 7c is a Fabry-Perot spectrogram of the Brewster-angled ruby laser. The distance between the FP mirrors was 3 cm, and that of the camera focus — 30 cm.

The spectral width of the emitted line was of the order of 0.1 Å. For a short ($\approx$ 1 m) or long ($\approx$ 2 m) resonator the number of longitudinal modes within this line-width was 80 and 160, respectively.



a

b

c

Fig. 7. a) Self-mode-locking of Brewster-angled ruby laser. Time base — 500 ns/full scale; b) giant pulse obtained from a ruby crystal with terminals perpendicular to the rod axis; c) FP interferogram of the emitted pulse

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