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The Self-Injected Non-Mode-Locked Picosecond Laser

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THE SELF-INJECTED NON-MODE-LOCKED PICOSECOND LASER

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ABSTRACT

A new type of laser which generates picosecond pulses is presented. 6ps ~ 1 GW, 3 pps, λ = 1.06 μm in a single pulse are obtained with good stability. Accurate timing of the pulses can be achieved and no external pulse selection is required.

In our laser the pulse doesn't develop from quantum noise but is the result of a nonlinear frequency and time processing in the cavity of a seed pulse that is coherent since the starting of the shortening process. We believe that the remarkable characteristics of pulse stability are at least partially due to these considerations in coherence.

§ 1 - Introduction

High power picosend light pulses have been generated in a number of ways [1-4]. Passive mode locking is the method that is most widely used in solid state laser applications and allows the production of bandwidth limited pulses of rather high intensity. The behavior of this kind of device has been extensively studied by various authors [1,2,5] and it has been shown that its stability and reproducibility are strongly affected by the intrinsically statistical origin of the short pulse formation process. For applications requiring pulse stability as well as an accurate pulse timing, other sophisticated techniques have been developed. For instance the externally-injected regenerative amplifier and the off-axis multipass amplifier allow the production of pulses with power and duration comparable to the ones obtained in passive mode locking but with far better stability characteristics [6-8]. With the regenerative amplifier the shorter duration pulses have been obtained using the technique of pulse compression with a saturable absorber [9]. With this scheme, compression by a factor 8 has been reported, resulting in a final pulse duration of 15psec.

In the present paper we report the first application of the regenerative compression technique to the self-injected (NdYAG--Nd glass) laser. In this type of laser, soon after the flash pumping action is started, the transmission of the optical cavity is conveniently modulated by a Pockels cell driven by a set of three square HV electric pulses. The timing and maximum voltage of these pulses is such that, after the Q-switch action is started, the amplification process in the cavity takes place on a "seed" optical pulse that can be far shorter (< 1ns) than the Q-switch pulse that would be extracted by the same laser in usual conditions (~ 35ns). This is the principle on which the laser self-injection effect (or cavity flipping) is based [10,11,]. In the configuration we describe in the present paper this seed pulse, during the amplification in the active medium, undergoes a further compression due to the nonlinear transmission of a saturable dye flowing in a cell inserted in the laser cavity. In this way we are able to reduce the typical 35 ns pulse duration of a normal Q-switched laser down to 6 ps, realizing an overall pulse shortening by about 3 orders of magnitude [12,13]. It is remarkable that the overall shortening process does not imply energy loss other than the one associated with dye saturation, i.e. corresponding to the final stage of pulse shortening (from ~ 1nsec to ~ 6psec) due to the nonlinear propagation in the dye. In fact we have demonstrated that for this kind of laser the application of the self injection pulse shortening process does not reduce the energy of the output laser pulse [11].

In this way very high peak power can be obtained, limited basycally by damage to the optical components and by effects of non-linear loss and self action arising in the active medium. In addition to that, the system has potentially good stability characteristics and, when required, a precise timing of the output pulse can be achieved. In the following sections of the paper we shall discuss separately the two different pulse shortening processes which take place in our device.

§ 2 - Subnanosecond pulse generation

The method of self-injection (or cavity-flipping) for short high peak power pulse generation is described schematically on the basis of the Figures 1 and 2). At time $t=t_0$ the voltage V applied to the Pockels cell (PC) is switched from $V_{\lambda/4}$ to 0 allowing the onset of the Q-switching oscillation (Fig. 2a). After an adequate delay $\tau = t_1 - t_0$ a $V_{\lambda/2}$ square pulse of duration T_g is applied to PC. If T_g has a convenient value, say one cavity round trip time $T_c = 2(L_1 + L_2)/c$, a seed pulse of duration $2L_2/c$ is generated in the cavity. This is the effect on which the cavity-flipping process is based [10, 11] . The duration of the seed pulse is determined by the size of L_2 as pointed out earlier. [11] In addition it can be controlled by the time T_g and by the voltage $V \neq V_{\lambda/2}$ of the V_g electrical pulse [14,15]. The minimum duration is limited by the rise time of the PC driving circuit, T_d, and can be found to be approximately 0,27 T_d [14]. The delay τ is determined by the seed to reach a sufficient high value of the ratio I peak/I background for the seed pulse [14,15]. In our laser the optimum condition for subnanosecond pulse generation was corresponding to the following values of the parameters: V_g= 9,5KV and $\tau \sim$ 50 ns. The seed pulse is regeneratively amplified by the active medium and, when it attains its maximum amplitude, it can be dumped out of the cavity at $t=t_2$ by applying a $V_d=V_{\lambda/4}$ step to PC. As the seed pulse can be made substantially short (<1ns) the output peakpower can attain large values.

In Fig. 2b the time evolution of the seed pulse circulating

in the cavity is shown schematically. Fig. 2c shows the dumped output pulse. It should be noted that if at $t=t_2$ the light pulse is travelling through the section L_2 of the cavity, i.e. between PC and mirror M_2, a single pulse is emitted for $V_d = V_{\lambda/4}$ as in Fig. 2c. The experimental results about the seed pulse evolution in our kind of laser are shown in fig. 3(a,b,d).

On the other hand, if at $t=t_2$ the seed pulse is in the section L_1, a couple of pulses apart by T_c will be emitted upon application of V_d=V (fig.3c). The relative intensity of the two pulses depends on which pulse of the train in fig. 2b is chosen to be dumped out first, keeping in mind that the second pulse is amplified once more in the active medium. These simplified considerations show that by a wise choice of the dumping out time we can obtain, in a reproducible way, a variety of operating conditions that improve the versatility of the device and can be very usefull for some experimental applications such as in incoherent or coherent (photon-echo) relaxation spectroscopy.

The experimental verifications of subnanosecond high power pulse generation by the self injection technique has been verified in our laboratory using Nd YAG [11] and Rhodamine 6G [15] as active media.

With a (6.3 x 60mm) NdYAG rod we have found experimentally that, when the self-injection and cavity dumping functions are activated, the peak pulse power is larger by a factor $\alpha = T_c/\Delta t_p$ where Δt_p is the output pulse duration. In our case we had: $\Delta t_p < 1ns$ (fwhm) and $\alpha \simeq 10$. With the pumping energy E_p = 110J, the output (cavity dumped) peak power was 80 MW. The shape and the peak power of the output pulses were stable to within 5% and the delay between Q-switching time (t_0) and the output pulse had a jitter lower than 0,5ns. This measurement has been carried out by multiple pulse superposition on CRT of a fast Tektronix 519 oscilloscope

It is remarkable that the same laser system with the same pumping conditions generates ~ 10nsec ~ 8MW optical pulses when the PC driver is set for normal Q-switching operation. This is the same energy which is associated with the subnanosecond pulse. Then our technique which can be applied to almost any conventional PC-driven Q-S. laser (equipped with R=100% end mirrors and double-escape GT prism) realizes a nearly adiabatic pulse shortening effect. This nearly complete adiabaticity in energy has nevertheless not been verified with our Rhodamine 6G dye laser. This is obviously due to the substantial population loss existing between successive round trips of the seed pulse in the cavity when the fluorescence time $\tau < T_C$. In our work the voltage of the gate pulse V_g must be set as close as possible to the extinction voltage . for the Pockels Cell in order to avoid background radiation that can be involved in the same amplification process affecting seed pulse. However we found that a complete background-free operation has not difficult to achieve in a stable and reliable way. The effect of the saturable dye helps in rejecting this background.

§ 3 - Picosecond pulse generation

The effect of pulse shortening which is achieved adiabatically by self-injection in a first step, can be pushed forward by orders of magnitude by simply inserting in the laser cavity of Fig.1 a saturable dye flowing cell. In this case we take advantage of the regenerative pulse shorten effect due to propagation in a non-linear saturable absorbing medium [9, 16, 17, 18].

In our laser [12, 13] a 6,3x60 mm NdYAG rod with AR coated end faces is pumped in a double elliptical cavity by a couple of simmered flashlamps. For our present application, the optical cavity was designed in such a way as to provide the adequate balance between the laser intensity seen by the active medium and by the saturable dye flowing in a cell (Fig.4). This is required by the different values of the gain and absorption cross sections for the two media, respectively, and by the need of reaching simultaneously a regime of saturation for both gain and absorption in order to obtain a good compression efficiency, [9, 16].

Two equally totally reflecting spherical mirrors with radii R_1 = 99,9 cm and R_2 = 67,5 cm determined the geometrical size of the cavity. With the geometrical parameters given in Fig. 4. the ratio of beam areas in the dye cell and in the rod was r ≃ 7,6.

This includes the effect of the Brewster angle tilting of the dye cell (DC) (thickness = 1mm). Due to rapid laser induced degradation of the dye it was found necessary to flow it through the cell. This one has been designed in such a way as to minimize turbulence effects in order to obtain good shot to shot reproducibility.

The dye we used was the Eastman-Kodak No. 9740 Q-switching solution in dichloroetane. The dye concentration was adjusted to an adequate value different from the one which caused self Q-switching and mode-locking in the laser. When only the Nd-Yag rod was operating in the cavity, the dye concentration correspond to a small signal transmission in the cell: $T=10^{-(0,47)}$. The Pockels Cell (PC) was a Lasermetrics 1057 FV driven by a kritron circuit capable of delivering the wave form which is necessary for a combined Q-switching, cavity flipping and cavity dumping operations. This multifunction operation using a single Pockels Cell was described in the previous paragraph. The schematic diagram of the kritron driving circuit is reported in Fig. 5.

The laser operated tipically at 3pps and the output was monitored by an ITL 1850 photodiode and a Tektronix 519 travelling wave oscilloscope. The overall rise time of the detection system was 320 ps. Ultrashort pulse duration measurements were performed by a standard triangular two photon fluorescence technique using the 5 cm cell filled with a 10^{-3} M/l solution of Rhodamine 6G in Methanol and by a background-free autocorrelator in a SHG KDP crystal [19]. The detailed autocorrelator curve will be reported in a forthcoming paper. Working with NdYAG only as active medium the laser was initially adjusted for operation under self-injection conditions by flowing pure dichloroetane through the dye cell. In this way the light pulse evolved in the laser cavity as a train of 2,5 ns pulses as shown in Figs. 6a and 6b, with the saturable dye flowing into the cell, we acted upon the flashlamp pumping voltage to find the condition of best pulse compression. This one has been found to correspond to driving the laser just above threshold. In this condition the pulse train of Fig. 6c was obtained. The two photon fluorescence pattern is shown in Fig.7 and corresponds to the highest pulse shown in Fig. 6c. Drawing the corresponding densitometric trace we have measured a pulse duration of 15ps. The contrast ratio obtained is 3:2. The peak power was found to be 0,9GW.

A further effect of pulse shortening has been obtained by inserting in the laser cavity a flashpumped ND glass (4mmx60mm) rod. In this configuration the NdYAG (3mmx50mm) rod was responsible for the low threshold generation of the seed pulse while the Nd glass rod provided large band amplification for further pulse shortening. Pumping of the glass rods was lower than required for the onset of laser oscillation in absence of the NdYAG medium. Working with a Q-100 KIGRE Nd-phosphate glass rod we obtained a pulses of 6ps duration. The pulse-to-pulse stability of the picosecond pulse has been assessed by simultaneous measurement by two phototubes of the energy of the pulse of λ=1,06μm and of the corresponding SHG pulse at λ=0,53μm. We found an energy stability of ~10%. Pulse-to-pulse fluctuations of the shape and length of the pulses where not detectable.

A very interesting feature of this system is a intracavity combined oscillation-amplification process which is determined by gain curves peaked at different wavelenghts (i.e.1,064 μm and 1,054μm for Nd YAG and - phosphate glass media). This should give rise to additional effects of pulse shaping [17, 18] . Details on the behaviour of this new, two media, picosecond laser will be given in a forthcoming paper.

The envelope of the pulse train shown in Fig. 6c which corresponds two only Nd YAG operation has a shape which is quite typical of the physical processes which are at the basis of the behaviour of our device [9, 16] . This shape can also give a fair indication of the good pulse shortening performance of the laser. The slow rise of the leading edge of the envelop at low pulse power indicates that the overall, low level, laser gain is small.

This is a condition for reaching the maximum intensity of the train with a large number of shortening passages. In our case the pulse made about 100 passages since the peak of the envelop of the Fig. 6c is delayed with respect to the self-injection operation by ~ 500 ns. In addition to that, in this regime, each passage of the pulse in the dye is more effective for compression since the pulse intensity is maintained in the range where the dye nonlinearity is stronger. It is very important not to saturate completely the dye in the first passages since the completely saturated dye has no pulse compression capability [9, 16, 20] . After the pulse reaches its maximum intensity, it falls down quite fastly since as the power decreases the dye gets less saturated and the cavity loss increases correspondingly.

The timing of the self-injection operation was found to be very important for obtaining good pulse compression. If self-injection is triggered too early, the initial seed pulse is not intense enough to start the process of dye saturation. On the other hand if the self-injection is triggered too late the seed pulse makes too small a number of compressing passages through the dye. In our laser, with only the NdYAG rod operating the delay τ of the gate pulse with respect to the Q-S. pulse, has been set to ~ 400nsec for optimum operation.

From the discussion above we can anticipate that high peak intensity and large pulse compression can be achieved with a carefull and somewhat critical adjustement of the following parameters: pumping level, dye concentration, ratio of intensities on the active and passive non-linear media and self-injection timing. A thorough analysis that elucidates the interplay of these competing effects will be reported elsewhere.

We wish to stress here the basic difference existing between our laser and the usual mode-locked lasers. In our system the pul se doesn't develop from quantum noise but rather is the result of a non-linear frequency and time processing in the cavity of a coherent seed pulse that keeps its coherence since the starting of the shortening process. Apart from obvious technical advantages (no need for Brewster cut rods and components) our device shows remarkable characteristics of pulse stability. This can be due to a combined effect of gain saturation in the dye and to, the above considerations on coherence. We can also understand the stability improvement offered by our system if we think that our device can be somewhat related to a combined passive/active mode locked laser, with 100% cavity-Q modulation. It has been recently verified that combined mode locking offers the best pulse stability performances in the picosecond regime [21].

§ 4 - Conclusions

In summary we have presented a new technique for production of high power picosecond pulses. In the present application we observed a pulse compression by a factor ~200 with respect to the normal self-injection operation, while the peak power gain in the compression process was ~ 70. This implied an energy reduction in this process by a factor of only ~ 3. The obtained short pulses were very stable and showed low jitter (± 10 ns) relative to the Q-switching HV pulse applied to the Pockels Cell.

At last, we have developed new type of picosecond laser which, in spite of its simple and quite conventional optical structure is based on concepts that are novel and, possibly far reaching. We believe that our device opens new perspectives in the field of laser physics and technology.

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Fig. 1

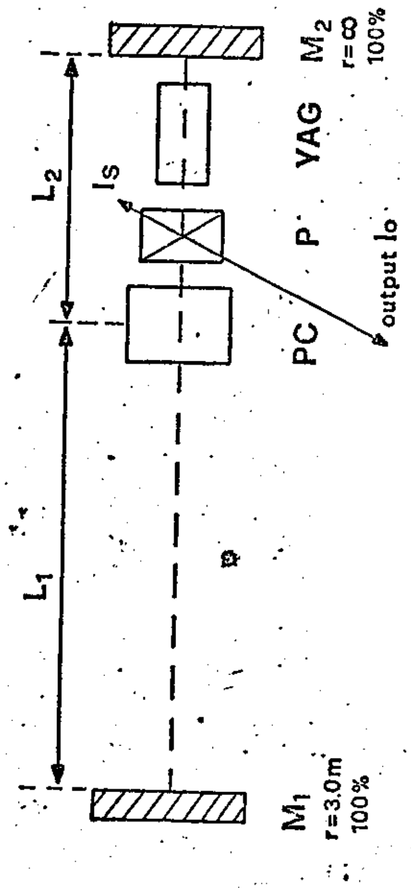


Fig. 2

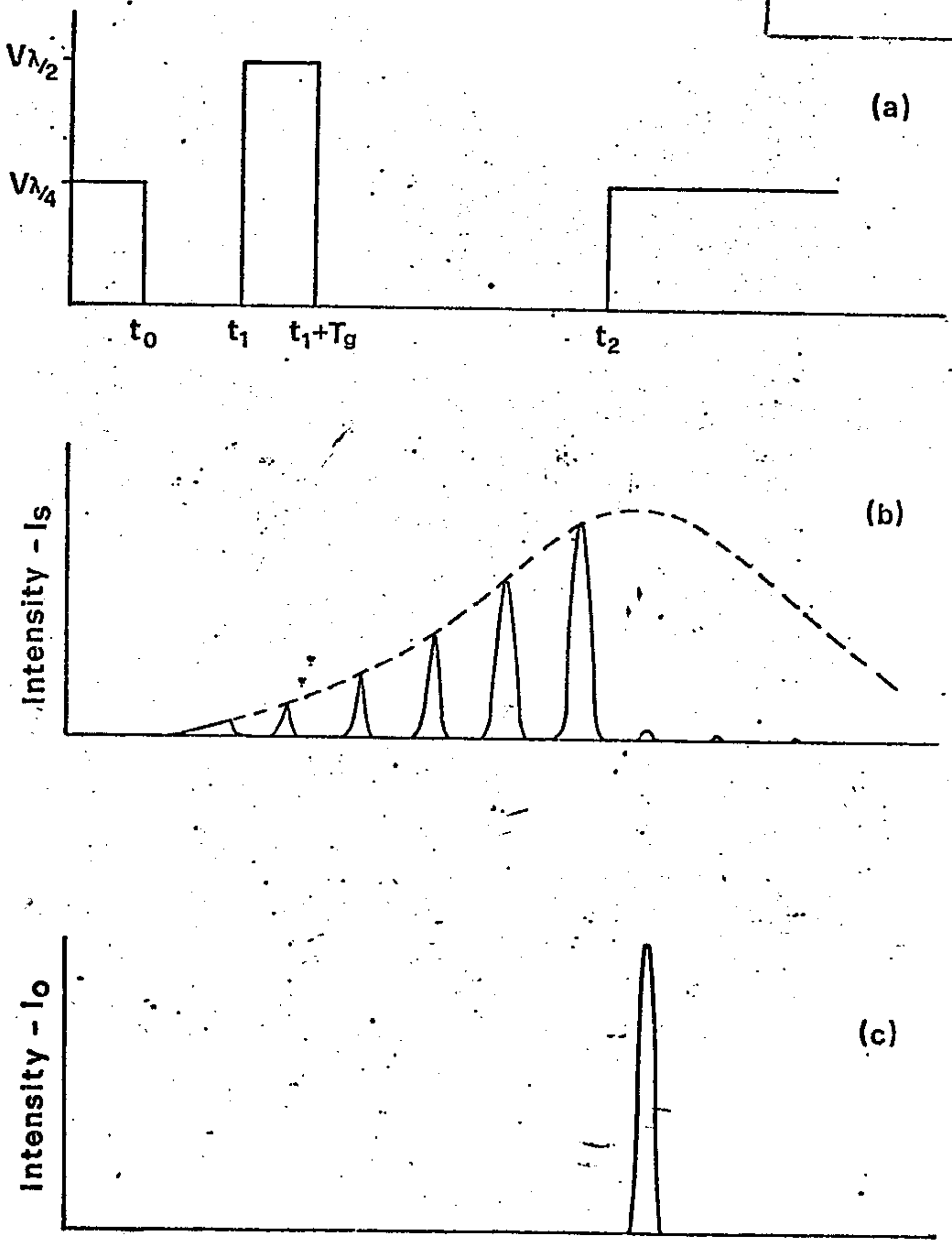


Fig 3

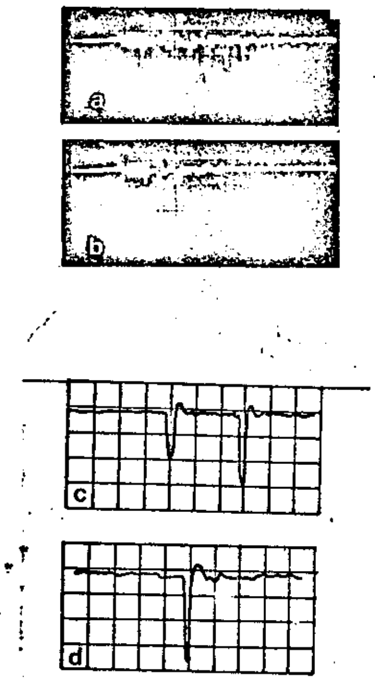
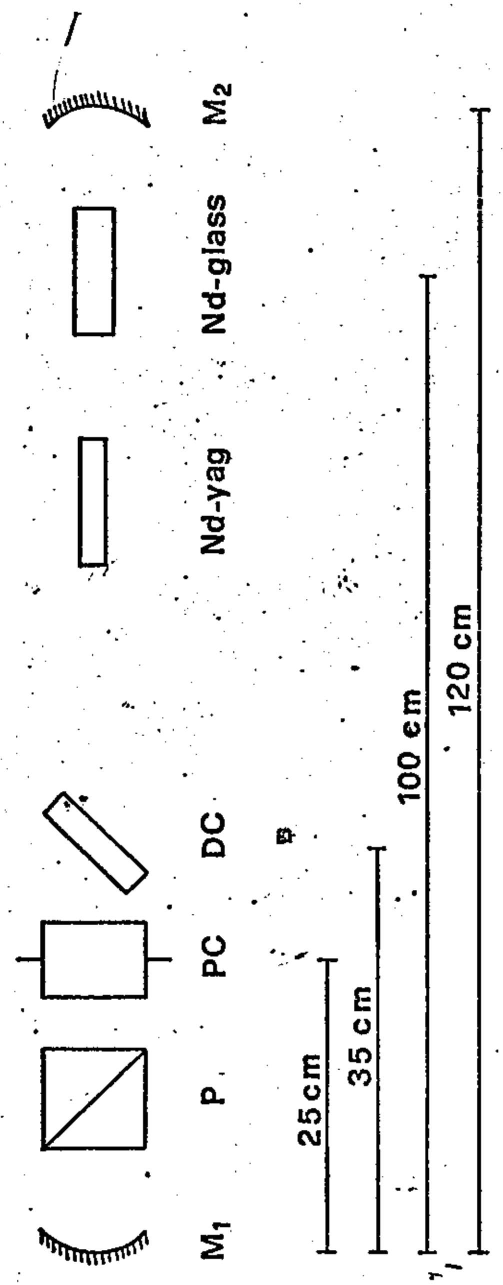


Fig. 4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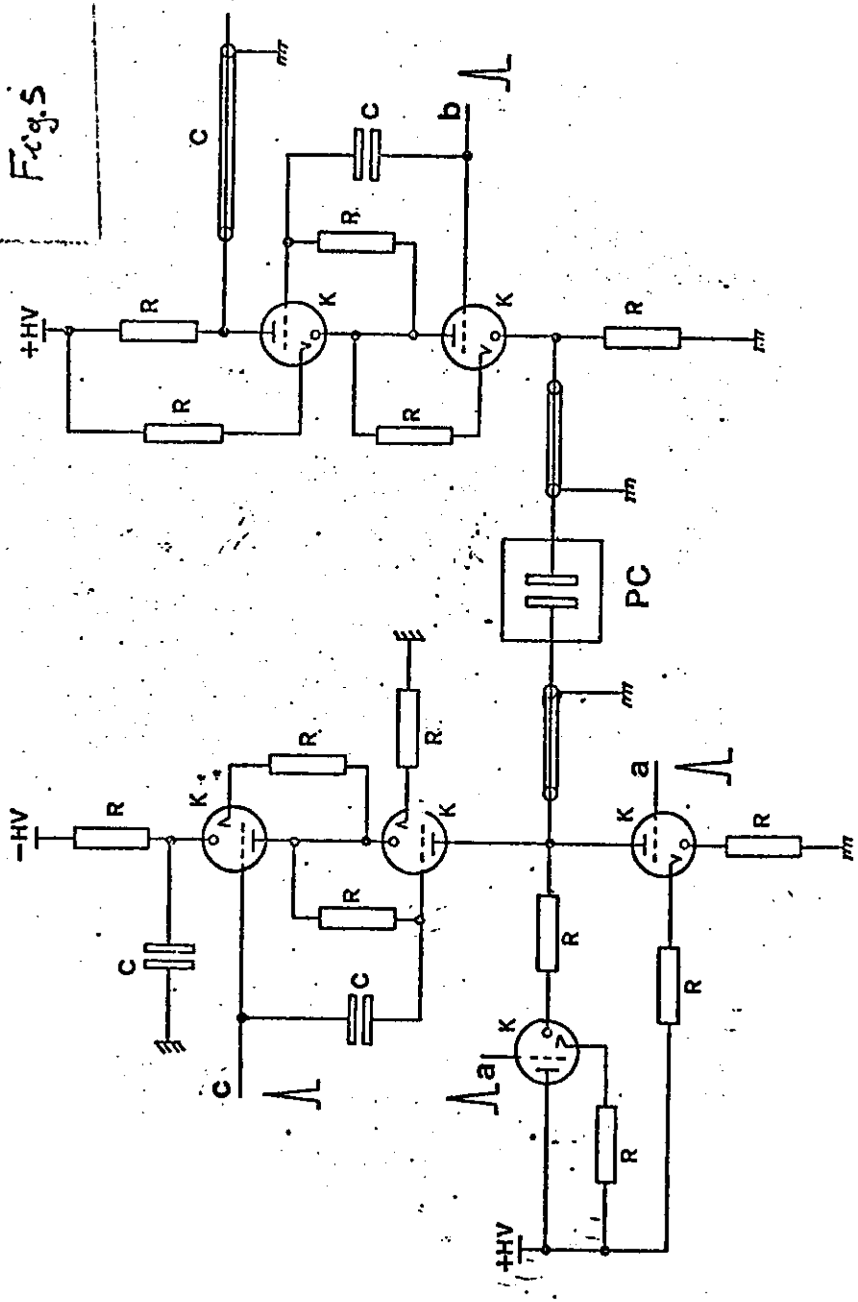
PC
DC
Nd-yag
Nd-glass
M2
25 cm
35 cm
100 cm
120 cm

Fig. 5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-HV
R
C
K
PC
a
b
c

Fig. 6

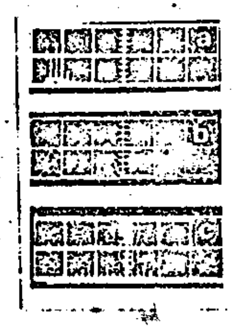

Fig. 7