Observation of compressed picosecond pulses of high repetition rate from a Nd-glass laser

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Picosecond pulses generated by a mode-locked neodymium-glass laser have been compressed down to 0.5 psec with a repetition rate up to 3×10^{11} Hz by the insertion of a glass flat inside the laser cavity. The reduction in pulse width is attributed to a frequency-dependent transit time on transmission through the glass flat.

It has been shown that the pulses emitted by the mode-locking Nd-glass laser are chirped, i.e., their frequency increases from the leading edge to the tail of a pulse almost linearly.[1] Moreover the later pulses in a train are longer than the earlier ones.[2] Both effects can be attributed to the dispersion of the Nd-doped glass used as the amplifying medium.

A dispersive structure which transmits the higher frequencies with greater velocity than the lower frequencies can reverse the chirping.[1] Using a series of gratings outside of the laser cavity Treacy succeeded in compressing the pulse to 4×10^{-13} sec.[1] Duguay and Hansen[3] were able to compress a chirped mode-locked He-Ne laser using a method suggested by Gires and Tournois.[3] The method utilizes the frequency-dependent interference obtained in multiple reflections by using a dispersive structure placed outside of the cavity.

In our experiments we have used the phase shift between the incident and transmitted beam introduced by multiple reflections in an optical flat placed inside the laser cavity to produce a time-compressed pulse. This method is only applicable when the time width of the pulse is greater than the transit time through the flat. When the pulse width is less than the transit time there will not be interference between the transmitted waves resulting from successive reflections since there will be no overlap of the transmitted waves.

The phase shift ϕ of a monochromatic wave of frequency ω, traveling through a glass flat, is given by $\mathrm{tg}\phi=[(R+1)/(R-1)]\,\mathrm{tg}(\omega t_0)$. Here R is the reflectivity of the glass-air interface and $t_0=nd\cos(\alpha)/c$, where d is the thickness of the flat, c is the velocity of light, α is the angle between the direction of light propagation inside the flat and the normal to the glass surface.[4] Assuming the refractive index n of the glass to be independent of frequency, the retardation time t' of a wave of frequency ω is given by

$$t' = -\frac{d\phi}{d\omega} = \frac{(1-R^2)t_0}{1+R^2-2R\cos(2\omega t_0)}.$$

Using the value $R=0.04$ which holds for normal incidence on glass of refractive index $n=1.5$ it follows from the above relationship that the maximum and minimum retardation times are $1.08t_0$ and $0.92t_0$, respectively.[5] To see whether this result can make up for the chirping caused by the dispersion in the laser rod, we have to compare it with the time delay of the different frequencies within the bandwidth of the pulses traversing the rod. Assuming a refractive-index variation of 0.00013 [6] over a bandwidth of 100 Å [7] we find for the difference in the traversal times of wavelengths 1.05 and 1.07 μ through a 15-cm long rod the value 0.065 psec. Thus it is seen that for instance a glass flat of thickness $d=1$ mm and $n=1.5$, yielding $t_0=5$ psec, can introduce a maximum difference in retardation times of $(1.08-0.92)\times10^5$ psec between the frequency components of the pulse. Thus such a flat is capable of compensating for the chirping due to the dispersion in the laser rod, provided the angle α is chosen properly. The transmission of such a flat varies only slightly with frequency; for $R=0.04$ it varies between 85 and 100%.

The laser cavity consisted of two plane-wedged dielectric mirrors of 65 and 99% reflectivity and a Brewster-cut Nd-doped glass rod (Kodak ND-11, length

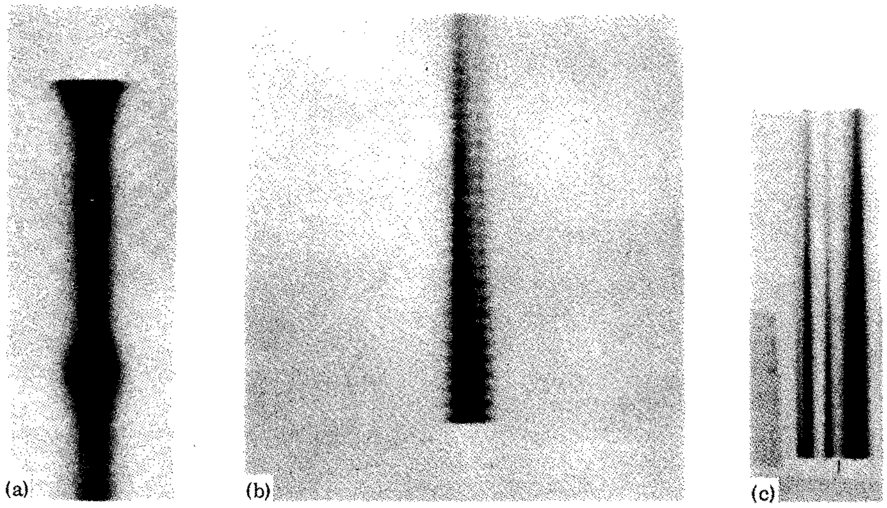

FIG. 1. Two-photon absorption display of the mode-locked Nd-glass laser output in a solution of Rhodamine B (mirror to the left): (a) without flat in the laser cavity, pulse duration 7 psec; (b) multiple pulses of 1.3-psec duration and 10^{11}-Hz repetition rate generated by a glass flat 1 mm thick; (c) multiple pulses less than 0.5-psec duration and 3×10^{11}-Hz repitition rate generated by a glass flat 0.33 mm thick.

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$6\frac{5}{8}$ in., diameter $\frac{3}{8}$ in.), which was pumped by a linear flashlamp in a cylindrical reflector of elliptical cross section. Even though this pumping configuration is very effective, the pumping is by no means uniform, so that the rod is distorted during the pumping process.[8] The laser was mode locked by a solution of Eastman No. 9860 dye in an Eastman Q-switch cell placed at the Brewster angle close to one of the mirrors.

The laser output, as observed by an ITT fast risetime photodiode and Tektronix 519-scope, consisted typically of a train of pulses separated by the round-trip time of the cavity (8 nsec).[7] However, the two-photon absorption technique[9] showed that each pulse viewed on the scope contained in most cases two or more pulses separated by the loop time between the Q-switch solution and the adjacent mirror [Fig. 1(a)]. The duration of these pulses varied from 5 to 10 psec. The insertion of a glass flat into the cavity at an angle of ~2° to the laser axis caused a dramatic change in the two-photon absorption display. Now a great many (sometimes more than 30) short pulses were produced, equally spaced by $2t_0$, the loop time in the flat [Fig. 1(b)]. We have demonstrated that the pulse separation corresponded exactly to the loop time in the flat by using flats of different thicknesses and refractive indices. The number of these pulses decreased in tilting the flat to greater angles. Near the Brewster angle multiple-pulse generation no longer occurred. This generation of multiple pulses occurred also without the insertion of any flat, if the Eastman cell with the Q-switch solution was placed nearly perpendicular to the laser axis, even though the windows of this cell are antireflection coated by the manufacturer.

It may be noted that the only effect on the scope tracing of the laser output was to reduce the number of pulses by roughly a factor of 3. In our experiments the pulse width was found to be either decreased or increased for different flat dimensions or orientations. This is to be expected from the sensitive dependence of antichirping or chirping on the angle of the flat to the incident pulse.

With a 1-mm glass flat in the cavity the pulse duration was reduced to about 1.3 psec [Fig. 1(b)]. In another experiment we obtained subpicosecond pulses, whose duration was shorter than 0.5 psec, at a repetition rate of 3.10 in. sec^{-1} [Fig. 1(c)]. Observation of the pulses of 0.5-psec duration was very critically dependent on alignment and not observed in every firing of the laser. In some cases the glass flat produced a broadening of the pulse to 15–20 psec. We attribute the pulse shortening and broadening to the antichirping and chirping effects, respectively, of the glass flat, as outlined above.

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[5] Under certain conditions the given consideration leads to group velocities greater than c, as is common in case of highly dispersive elements. However for a rough estimate of the effects to be expected we may use this simple treatment.

[6] This value has been interpolated from the values 1.5099 at 1.014 μ and 1.5084 at 1.129 μ, which hold for the Nd-doped glass LG-56 from Jenaer Glaswerk Schott in Mainz (West Germany). The dispersion of other Nd-doped glasses should not differ markedly from these values.

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