# High-efficiency pulse compression with intracavity Raman oscillators

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High-efficiency pulse compression has been obtained by using an intracavity Raman oscillator. The energy of a primary laser stored in its high-$Q$ cavity is extracted at the Stokes frequency by means of a Stokes laser having a high Raman gain and a low-$Q$ cavity. This technique, using hydrogen gas as the Raman medium, permits shortening of the pulse duration of a ruby laser by a factor of 6.7 with 87% effective quantum efficiency. It would be especially useful with low-gain (alexandrite) and with short-storage-lifetime lasers.

Short-duration laser pulses are useful for various laboratory investigations, such as studies of relaxation, plasma generation, and nonlinear phenomena, or for industrial applications (such as laser-fusion projects and laser telemetry).

To obtain lasers operating in the nanosecond range, several methods are used. First, there are $Q$-switched lasers, but only a few of them can deliver pulses as short as a few nanoseconds. A typical technique for short-laser-pulse production consists of assembling a $Q$-switched oscillator, a pulse shaper slicing a part in the oscillator pulse, and amplifiers to obtain enough energy in the final stage. This technique may be efficient but is rather cumbersome when applied to the case of low-gain laser media, such as alexandrite, or for media in which the lifetime of the excited state is shorter than the pumping-pulse duration (dye or excimer lasers, for example).

Another scheme uses cavity dumping of the photons stored in a high-$Q$ laser cavity by means of an electro-optical switch,[1] which makes this method difficult and expensive.

Recently other solutions were proposed that use nonlinear optics and particularly backward-stimulated Brillouin scattering[2] or backward-stimulated Raman scattering (BSRS).[3] When the BSRS method was used, pulse compression by a factor of 5 with 40% quantum efficiency was achieved in the case of excimer lasers.[4] Nevertheless, these performances are tied to the spectral purity of the input laser because of the competition between backward and forward Raman gain.[5] Moreover, this technique requires a long Raman cell and a low divergence beam, and the quantum efficiency seems to be limited.

In this Letter we report on a simple technique using an intracavity Raman oscillator (ICRO) to obtain high-efficiency pulse compression. Intracavity stimulated Raman scattering (SRS) has been studied in the past[6] but only to produce a lower threshold for the SRS process. In our scheme the basic idea is to extract the energy of a primary laser cavity at the Stokes frequency during a short time by using two overlapping cavities. A high-$Q$ laser cavity is used to store the electromagnetic energy without important losses. When the energy is maximum in the laser cavity, the Raman gain in an intracavity Raman medium exceeds threshold, and the Raman laser acts as a passive cavity dump for photons stored in the primary laser cavity. As the gain at the Stokes frequency is high, the rise time of the Stokes pulse is fast. Furthermore, if the Raman cell is simultaneously located inside a low-$Q$ cavity, the Stokes energy will be extracted in a time of the order of a cavity round trip.

This simple concept was demonstrated by using a ruby laser as the primary source and compressed hydrogen gas as the Raman medium. The experimental setup of the ICRO is shown in Fig. 1. There were two different cavities, which operated at the ruby frequency (14 404 cm$^{-1}$) and at the Stokes frequency (10 249 cm$^{-1}$), respectively. The ruby cavity consisted of a concave mirror $M_1$ ($R$ = 5000 mm) and a flat mirror $M_4$, both having 100% reflectivity in normal-incidence operation, and two 95% reflectivity mirrors $M_2$ and $M_3$ used at 45° incidence angles. The laser head was located between $M_1$ and $M_2$, and a $Q$-switched system placed between $M_3$ and $M_4$ consisted of a Pockels cell operating in the $\lambda/2$ regime and a Brewster-angle glass-plate polarizer. The hydrogen Raman medium was contained in a high-pressure cell with windows at the Brewster angle placed between $M_2$ and $M_3$. Losses in the ruby cavity were estimated to be about 30%. This corresponds to a 55-nsec decay time for the energy in the laser cavity. By using more appropriate (100% reflectivity) mirrors at $M_2$ and $M_3$ and antireflection-coated optics, it would be possible to reduce these losses to a few per cent and so considerably lengthen the photon lifetime in the laser cavity. Aperture $D_1$ corresponding to the aperture of the Pockels cell, restricted the beam diameter of the ruby to 5 mm. The Stokes cavity was formed by the 100% reflectivity mirror $M_5$ and by mirror $M_6$ ($R$ = 4%). Mirrors $M_2$ and $M_3$ transmitted about 97% each at the Stokes frequency. As the Raman gain is pressure dependent in the range of interest, the hydrogen-filled cell was composed of two identical parts

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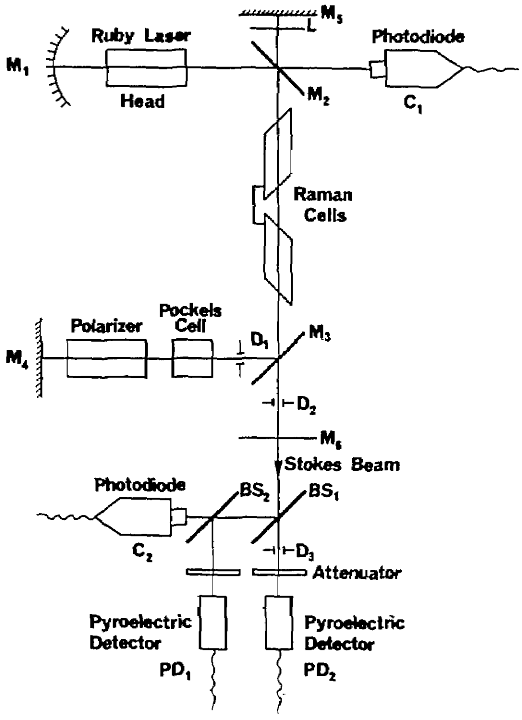


Fig. 1. Experimental setup: $M_1$–$M_6$, dielectric-coated mirrors; $BS_1$ and $BS_2$, beam splitters; $D_1$–$D_3$, apertures; L, convergent ($f$ = 5 m) lens.

with Brewster angles set in a complementary way; this construction permits varying hydrogen pressure without there being misalignments caused by the refractive-index variations of the gas. Aperture $D_2$ restricted the Stokes beam diameter in the cavity to 5.5 mm. In order to reduce the beam divergence, a concave mirror $M_5$ would have been useful. As it was unavailable at the time of the experiment, a 5-m focal-length lens L was inserted between $M_5$ and $M_2$ for this purpose.

Photodiode $C_1$ allowed us to observe the temporal behavior of the ruby laser inside the cavity. A small part of the Stokes beam (3%) was reflected by beam splitter $BS_1$ and further separated into two parts by beam splitter $BS_2$. In this way we could both monitor the temporal shape of the Stokes beam by using photodiode $C_2$ and obtain an energy reference with pyroelectric detector $PD_1$ (Gen Tech Model ED 200). Iris aperture $D_3$ was located 1.3 m away from $D_2$ and permitted, when used with pyroelectric detector $PD_2$ (Gen Tech Model ED 200), measurement of the divergence of the Stokes beam.

All the results reported here were obtained with a 530-J electrical input in the flashlamps pumping the ruby rod and at 20-atm hydrogen pressure in the Raman cell. With such electrical excitation and without Stokes mirrors $M_5$ and $M_6$, the maximum energy efficiency for the ruby laser was reached by using a 52% reflectivity exit mirror instead of $M_4$. Pulse duration at half intensity was then 40 nsec, and the ruby energy 260 mJ. At the same electrical excitation and with 100% reflectivity mirror $M_4$, the ruby pulse was shortened to about 30 nsec, as shown in Fig. 2(a), but no energy could be extracted from this two-100%-reflectivity-mirror cavity.

When Stokes cavity $M_5$–$M_6$ was restored, the ruby pulse was strongly depopulated, as shown in Fig. 2(b). As expected, this gave rise to a short-duration Stokes pulse [see Fig. 2(c)].

Performance of this Raman laser is summarized in Table 1. The Stokes energy was very stable (160 mJ with a rms deviation of 8 mJ). When compared with the 260-mJ maximum energy available with the ruby laser, this Stokes energy corresponds to a very high effective quantum efficiency of 87%; almost all ruby photons in the cavity were thus transferred to the Stokes beam. The Stokes-pulse duration was 6.0 ± 0.6 nsec. At this point it is important to note that the shape reproducibility of the Stokes pulse depended strongly on the alignment of the ruby-laser cavity. This was probably due to transverse inhomogeneities in the ruby beam, which caused the Stokes threshold to vary in time from one position to another in the beam. As a general rule, the mechanical cavity stability must be high in order to get a good temporal shape reproducibility. Although no special care was taken to maintain a high-quality stability, more than 80% of the Stokes pulses were similar in temporal profile. The 6-nsec pulse duration may be compared with the round-trip times in the Stokes (5-nsec) and ruby-laser (8.7-nsec) cavities. It appears that the Stokes energy is extracted in a time shorter than the round trip in this ruby-laser cavity. With such energy and pulse duration, the compression rate is 6.7 with 87% quantum efficiency

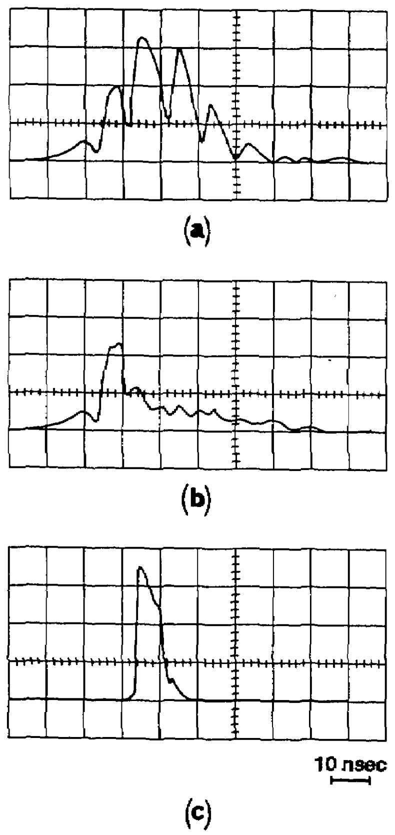


Fig. 2. Pulse profile of the ruby laser (a) without and (b) with the Stokes cavity and (c) of the Stokes laser. Vertical scale is the same for (a) and (b) and is not related to that of (c).

Table 1. Stokes Laser Performance at 10 249 $cm^{-1}$ [a]

| | |
|---|---|
| Energy | 162 mJ |
| Pulse duration | 6 nsec |
| Power | 27 MW |
| Intensity | 113 $MW/cm^2$ |
| Beam divergence | 80% energy in 2 mrad, 60% energy in 1 mrad |

[a] The excitation source is a ruby laser pumped by 530-J flash-lamps.

when set against the optimum ruby-laser performance described above. These values compare favorably with results obtained by BSRS.[4] The beam divergence was found to have the following characteristics: 80% of the Stokes energy was contained in a 2-mrad angle and 60% of this energy in a 1-mrad angle. Under our experimental conditions, an occasional second Stokes beam also appeared there, but its energy was always less than 1 mJ.

In conclusion, we have demonstrated a new technique of pulse compression by using an intracavity Raman oscillator. This technique offers several advantages over the BSRS method, such as higher quantum efficiency, less-cumbersome experimental systems, and less-severe requirements with respect to the spectral purity of the pump laser.

It also offers cost advantages over the classical cavity-dumping method because in our case the cavity is dumped passively without an expensive active electro-optical switch.

Without mirrors forming the Stokes cavity, this arrangement can also be used as an intracavity Raman amplifier (ICRA). Our recent calculations show that one-pass energy extraction from an ICRA may produce much shorter pulses (2–3 nsec) with the same high quantum efficiency. Experiments are in progress to demonstrate such a system. Work is also in progress to obtain a few-nanosecond second Stokes pulse by simultaneously using three overlapping cavities.

Let us underline in a final statement that in the technique described above photons present in the laser cavity and not the excited-state population of the laser medium represent the true energy storage. Such a scheme can, therefore, be applied to any laser. It would be especially useful in the case of lasers that cannot deliver short pulses. This is particularly true for low-gain lasers (alexandrite lasers) and for short-storage-duration laser media.

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