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Inexpensive high-speed dentist drill light chopper and its use in rejecting luminescence background from Raman spectra*

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An inexpensive dentist drill laser beam chopper is described. The chopper, which can be tuned for a chopping frequency from 100 Hz to 400 kHz, is compact, stable, and easily constructed. The usefulness of the dentist drill laser beam chopper is demonstrated in a technique for the suppression of luminescence background in Raman spectra. The technique is shown to be capable of almost complete suppression of luminescence with decay lifetimes greater than 10^{-6} sec.

Many commercially available lock-in amplifiers are capable of amplifying signals modulated at frequencies up to 250 kHz, but presently available commercial mechanical light beam choppers have a maximum chopping frequency of less than 10 kHz. We have developed an inexpensive, compact, high-speed mechanical laser beam chopper which can be tuned for a chopping frequency from 100 Hz to 400 kHz, thus producing modulated signals covering and exceeding the frequency range of commercial lock-in amplifiers.

The high-speed dentist drill chopper which was specifically designed to chop a focused laser beam has several useful applications such as mechanical Q-switching of lasers, pulsed Raman spectroscopy, and use as a high-speed stroboscope. We shall demonstrate the usefulness of the mechanical laser beam chopper in a new technique to suppress luminescence that often masks Raman spectra. We will show that this technique is capable of almost complete luminescence suppression for materials that exhibit long-lived luminescence (lifetime greater than 10^{-6} sec).

To our knowledge there have been no other successful attempts to mechanically chop light beams in the frequency range of greater than 50 kHz, but a rotating prism driven by a dentist drill has been used to produce 7 kHz pulses of laser light with nanosecond rise times.[1] High rotational speeds have also been obtained in turbine-driven rotating mirror assemblies used with cameras designed for time magnification.[2] The turbine-drive rotating mirrors have been operated at up to 10 000 rps. To obtain this rotational speed the turbine was driven by helium gas and the mirror rotated in a helium atmosphere. When the turbine was driven by air and the mirror rotated in an air atmosphere, the maximum rotational speed was approximately 7000 rps. The success in obtaining high rotational speeds through turbine drives suggests their use to drive a light chopper.

Shown in Fig. 1 is the high-speed mechanical light beam chopper. It consists of an air turbine dentist drill[3] with an 80-tooth, 12.7-mm diam clock gear as the laser beam chopping blade. The clock gear was carefully soldered (using soft solder) to a stainless steel rod which fit into the collet of the dentist drill. The dentist drill has a top rated speed of ~300 000 rpm (5000 rps) when driven by air at 2-atm pressure and rotating in an air atmosphere. With the 80-tooth gear as the chopping blade a maximum chopping frequency of 400 kHz was obtained when the drill was driven by N_2 gas at a pressure of ~2.6 atm. By varying the pressure and using different chopper blades, the chopping frequency can be varied from 100 Hz to 400 kHz. The chopping frequency stability shows considerable dependence on the gas control. By controlling the pressure with a gas flow valve connected to a regulated N_2 gas bottle, a frequency stability of better than 1 % was obtained.

Oscilloscope traces of the response of a photodiode to the chopped laser beam are shown in Fig. 2. The traces demonstrate the peak-to-peak intensity uniformity and frequency stability characteristic of a laser beam chopped by the dentist drill chopper. The actual square-wave profile of the chopped beam is not observed owing to time constant effects in the photodiode circuit. Since the laser beam can be focused to a spot size of ≤50 μm, on the 80-tooth chopping blade, a pulse rise-

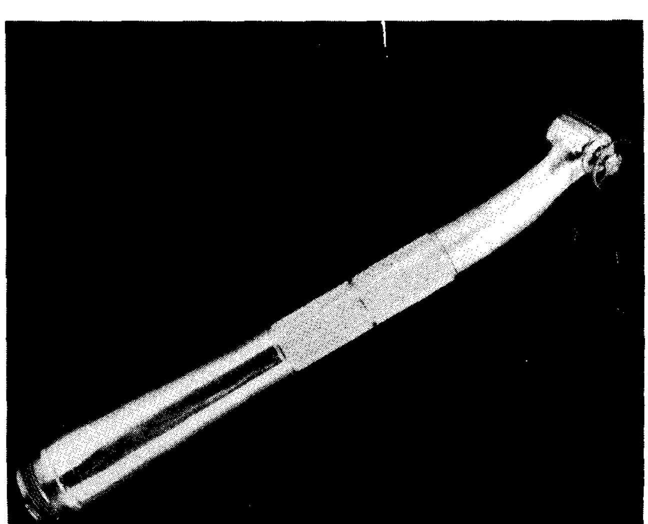

FIG. 1. The high-speed mechanical laser beam chopper.

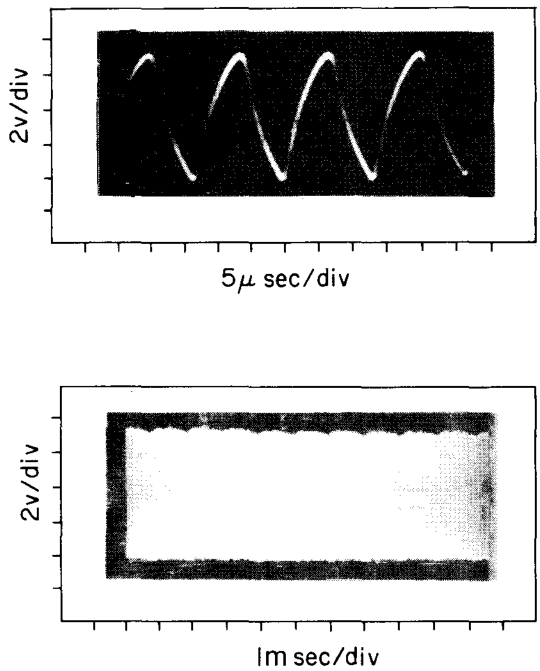

FIG. 2. Oscilloscope traces of the response of a photodiode to the chopped laser beam for $f = 80$ kHz.

time of less than 20% of the pulse width is easily obtainable. Also, if a 12.7-mm-diam blade was made with 100-μm slots, a chopping frequency of greater than 1 MHz could be obtained. The dentist drill chopper which modulates the laser beam to form approximately square pulses separated from each other by the width of one pulse is quite compatible with commercial lock-in amplifiers. Moreover, by way of comparison with commonly used commercial acousto-optic shutters[4] for lasers the dentist drill chopper is considerably less expensive and is not limited to any particular wavelength range.

To demonstrate one use of the dentist drill chopper, we describe here a high-speed chopping technique which utilizes the chopper and a commercial lock-in amplifier for the suppression of luminescence background in Raman spectra. Recently, two pulsed laser techniques[5,6] which were based on the different lifetimes of the luminescence (greater than 10^{-10} sec) and Raman scattering processes ($\sim 10^{-14}$ sec) have been used to suppress the luminescence background. Both techniques employed relatively expensive apparatus which included sophisticated electronics and either a Q-switched Nd:YAG laser or a mode-locked Ar ion laser. The mode-locked laser technique is capable of suppressing luminescence with lifetimes from 10^{-7} to 10^{-9} sec[5] and the Q-switched Nd:YAG system can be applied to luminescence with lifetimes greater than 10^{-7} sec,[6] while the technique described here is capable only of suppressing luminescence with lifetimes greater than 10^{-6} sec. It is important to note that while almost all organic liquids and most solid luminescent materials have lifetimes less than 10^{-7} sec, some solids, especially those with laser capabilities, have longer luminescence lifetimes.

The high-speed chopping technique utilizes the mechanically chopped laser beam to excite the Raman spectra of the sample. When the exciting laser radiation is chopped at a frequency greater than the inverse of the luminescence lifetime but less than the inverse of the Raman lifetime, the Raman intensity will be modulated at the chopping frequency while the luminescence will exhibit an approximately constant intensity (due to a much slower response). Commercial lock-in amplifiers are well suited to separate modulated and unmodulated signals; a lock-in amplifier tuned to the chopping frequency will selectively amplify the Raman signal while the "constant" luminescence signal will be suppressed.

To understand the quantitative features of this luminescence suppression technique, the luminescence response to a square exciting pulse must be considered. When the intensity of the exciting radiation is changed sharply, the corresponding luminescence response is often exponential.[7] When the exciting radiation is turned off the luminescence intensity, $I(t)$, decays as

$$I_d(t) = I' \, e^{-(t/\tau_d)}. \tag{1}$$

For this case I' is the luminescence intensity at $t = 0$, and τ_d is the decay time. When the exciting radiation is turned on the luminescence intensity can be represented as

$$I_r(t) = I_0 - (I_0 - I') \, e^{-(t/\tau_r)} \tag{2}$$

where I_0 is the saturation luminescence for cw excitation, and τ_r is the characteristic rise-time.

When chopped radiation excites luminescence, a steady state condition will be reached in which the

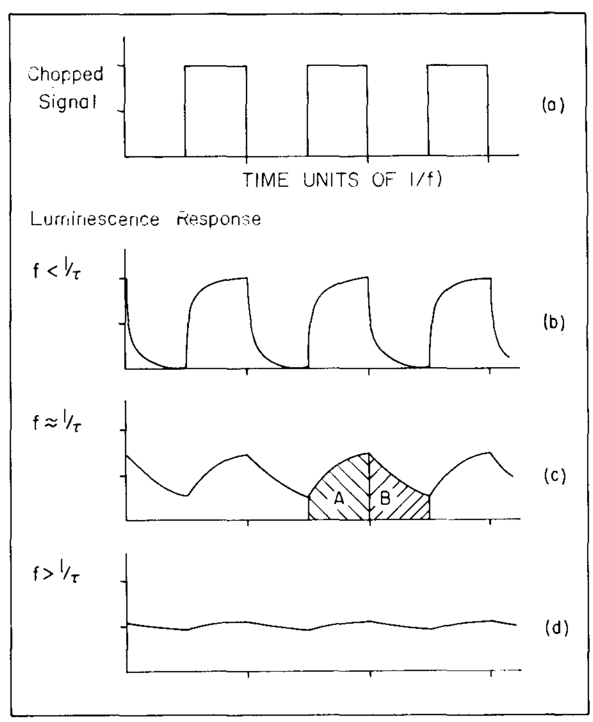

FIG. 3. A representation of the luminescence response to a square wave exciting signal—(a); for $f < 1\tau$—(b); $f \approx 1/\tau$—(c); and $f > 1/\tau$—(d).

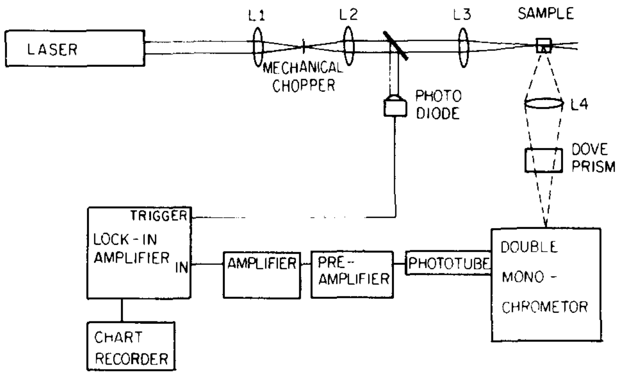

FIG. 4. The experimental configuration and detection electronics used in the new technique for suppression of luminescence background in Raman spectra.

luminescence intensity rise during the "on" time is equal to the intensity decay in the "off" time. A representation of the steady state luminescence response to a square-wave exciting signal for a material for which $\tau_r \approx \tau_d$ is shown in Fig. 3. The intensity as a function of time for an ideal chopped beam is indicated in Fig. 3(a). The luminescence response to the indicated exciting signal chopped at frequencies $f < 1/\tau$, $f \approx 1/\tau$, and $f > 1/\tau$ is shown in Figs. 3(b), 3(c), and 3(d), respectively.

A lock-in amplifier will separate and amplify the component of that signal that is modulated at the chopping frequency while suppressing the remainder of the input signal. If the signal indicated in Fig. 3(c) was the input to a lock-in tuned to the chopping frequency, the lock-in output would be proportional to the difference of the areas A and B. Thus for $f < 1/\tau$ the lock-in amplifier would suppress little of the luminescence signal, but for $f \approx 1/\tau$ a significant portion of the luminescence would be suppressed, and for $f > 1/\tau$ almost complete luminescence suppression would be achieved.

Assuming the exponential response of the luminescence indicated in Eqs. (1) and (2), the theoretical luminescence suppression factor (LSF) as a function of chopping frequency can be obtained. We define the LSF as the ratio of the luminescence intensity from cw laser excitation, $L(0)$, to the luminescence intensity not suppressed by the lock-in amplifier, $L(f)$, when the system is excited by a chopped laser beam at frequency f. For a luminescence signal such as that shown in Fig. 3(c) the LSF is

$$L(0)/L(f) = I_0/(A - B)f \tag{3}$$

By solving for the integrated intensities A and B using Eqs. (1) and (2) and the assumption that a steady state condition is reached, Eq. (3) becomes

$$\frac{L(0)}{L(f)} = \left\{\frac{1}{2} - f(\tau_r + \tau_d)\left[\frac{\{1 - \exp[-1/(2\tau_d f)]\}\{1 - \exp[-1/(2\tau_r f)]\}}{\{1 - \exp[-(\tau_r + \tau_d)/(2\tau_r\tau_d f)]\}}\right]\right\}^{-1}. \tag{4}$$

For many solids fluorescence rise- and decay-times are approximately equal.[7] For that case the LSF is ~20 when the chopping frequency is equal to $(\tau_d)^{-1}$, and the LSF is greater than 75 for a chopping frequency of $2(\tau_d)^{-1}$. It is important to point out that while the luminescence is suppressed by the lock-in amplifier, the Raman intensity is independent of chopping frequency and equal to ½ that obtained with cw excitation.

The experimental configuration and detection electronics which were used to suppress luminescence background in Raman spectra are shown in Fig. 4. The scattered light was collected at 90° from the incident beam and dispersed with a J.A. 1-m double monochromator. A glass slide was used to deflect about 5% of the chopped beam. The deflected beam was detected by an EG&G SGD 040L silicon photodiode.[8] A PAR HR-8 lock-in amplifier[9] which was triggered by the signal from the photodiode was used to amplify the Raman signal and suppress the unmodulated luminescence.

We found that ruby ($Al_2O_3:Cr^{3+}$) was an ideal material to test the luminescence suppression capabilities of the system described above. Ruby has an intense luminescence band centered at 6943 Å, the lifetime of which is about 5 msec.[10] The upper trace in Fig. 5 is the Raman spectrum of ruby obtained using conventional dc photon counting electronics while the lower spectrum was obtained using the lock-in system. The spectra of Fig. 5 were taken using argon ion 5145-Å laser radiation chopped at 89 kHz.

Both traces were recorded with the same scan speed and time constant (2 sec). The scattering geometry which was $x(zz + zx)y$[11] with $z\|c$ allowed observation of all seven Raman active modes of the Al_2O_3 lattice.[12] While both spectra clearly exhibit the seven Raman lines, the broad Cr luminescence band is shown only in the spectra obtained using dc photon counting electronics. The lock-in amplifier completely suppresses the luminescence of the Cr ions.

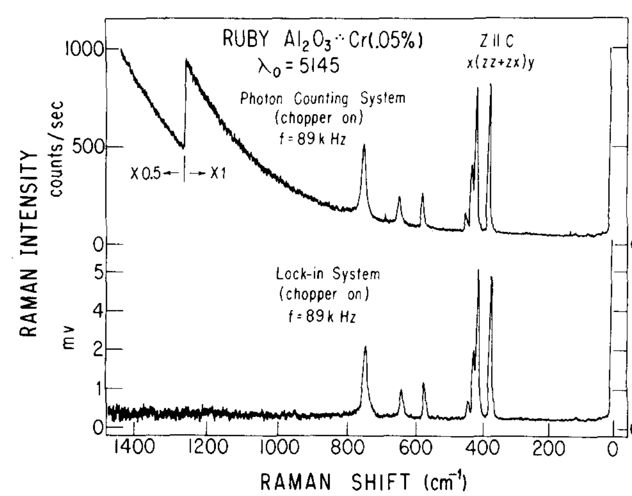

FIG. 5. Raman spectra of ruby ($Al_2O_3:Cr^{3+}$). The top trace was recorded with dc photon counting electronics while the lower trace was recorded using a lock-in amplifier. The abscissa is linear in wavelength, not wavenumber.

To test the luminescence suppression capabilities of this system in a region of higher luminescence intensity, chopped 5682-Å Kr ion laser radiation was used to excite the Raman spectrum of ruby. When the Raman spectrum is excited by longer wavelength radiation, the Raman lines are also shifted to longer wavelength. By using 5682-Å Kr ion laser excitation instead of 5145-Å excitation the Raman lines can be projected onto the strong ruby fluorescence band. The Raman spectrum obtained with the chopper lock-in system using 5682-Å Kr ion laser excitation is shown in Fig. 6. The strongest Raman lines of the Al_2O_3 lattice yield signals of ~600 cps at ~400 cm^{-1} and are clearly evident while the fluorescence background, which is more than 200 times more intense, is completely suppressed.

The frequency dependence of the LSF predicted in Eq. (4) is compared to the observed frequency dependence for ruby in Fig. 7. The ruby fluorescence rise- and decay-times of 1.5 and 4.5 msec, respectively, which were used to calculate the predicted luminescence suppression factor, were measured using a boxcar integrator. The results shown in Fig. 7 indicate that the experimental luminescence suppression system described here achieves the theoretically predicted LSF.

Although most luminescent materials have lifetimes less than 10^{-7} sec, necessitating the application of the mode-locked laser technique for luminescence suppression, the mode-locked laser technique cannot be used to suppress long-lived luminescence. Also while the pulsed laser techniques have yielded a decrease of less than a factor of 30 in the ratio of background luminescence to Raman signal, we observed here a decrease of that ratio by a factor greater than 1000. Though the signal-to-noise ratio, S/N, of spectra obtained with the chopper lock-in technique is not improved with respect to the S/N of spectra obtained using cw laser excitation, the pulsed laser techniques are expected to yield an increase in the S/N. However, the predicted increases in Raman S/N with pulse techniques are not realized in practice because of pulse-to-pulse nonuniformity and triggering irregularities.[5]

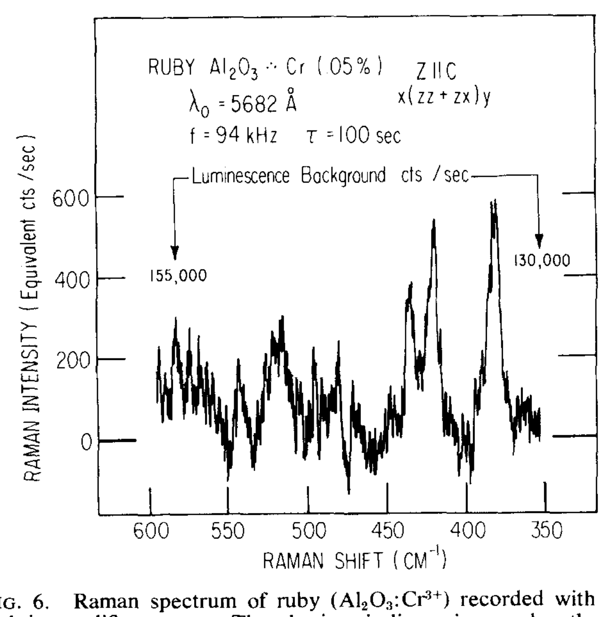

FIG. 6. Raman spectrum of ruby (Al_2O_3:Cr^{3+}) recorded with the lock-in amplifier system. The abscissa is linear in wavelength, not wavenumber.

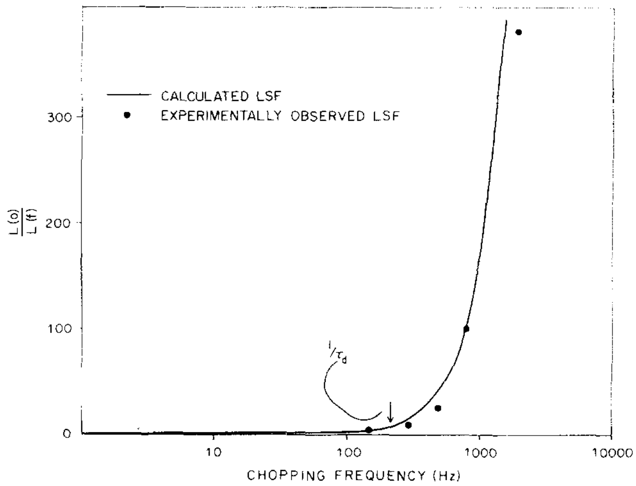

FIG. 7. Luminescence suppression factor for ruby as a function of chopping frequency. The solid line is the calculated LSF while the solid circles are the observed LSFs of the chopper lock-in system.

We have shown that the dentist drill chopper can be used to suppress luminescence background in Raman spectra, but the possibility of its use to Q-switch both gas and solid state lasers may be an equally important application. Hwang and Solin[13] have shown that it is possible to use a commercial mechanical light beam chopper to Q-switch a CO_2 laser, but Q-switching solid state lasers such as Nd:YAG should also be possible with the high-speed dentist drill chopper.

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[1] G. W. Hoffmann and T. M. Jorin, Appl. Opt. **10**, 218 (1971).
[2] W. E. Buck, Rev. Sci. Instrum. **25**, 115 (1954).
[3] Mini Mite dentist drill from Electro Dent Inc., 120 Haddon Towne Court, Cherry Hill, NJ.
[4] For example, Coherent Radiation Laboratories, model 462 acoustic shutter.
[5] R. P. Van Duyne, D. L. Jeanmarie, and D. F. Shriver, Anal. Chem. **46**, 213 (1974).
[6] P. P. Yaney, J. Opt. Soc. Am. **62**, 1297 (1972).
[7] B. DiBartolo, *Optical Interactions in Solids* (Wiley, New York, 1968).
[8] EG&G Inc. Electro-optics Div., 35 Congress St., Salem, MA 01970.
[9] Princeton Applied Research Corp., P.O. Box 565, Princeton, NJ 08540.
[10] T. H. Maiman, Phys. Rev. Lett. **4**, 564 (1960).
[11] For explanation of Raman notation, see T. C. Damen, S. P. S. Porto, and B. Pell, Phys. Rev. **142**, 570 (1966).
[12] S. P. S. Porto and R. S. Krishnan, J. Chem. Phys. **47**, 1009 (1967).
[13] D. M. Hwang and S. A. Solin, Phys. Rev. B **9**, 1884 (1974).