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COMPARISON OF RAMAN AND DEGENERATED OPTICAL PARAMETRIC OSCILLATORS FOR AHIGH-ENERGY AND HIGH-REPETITION-RATE EYE-SAFE LASER

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Comparison of Raman and degenerated optical parametric oscillators for a high-energy and high-repetition-rate eye-safe laser

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Abstract. A high-pressure laminar flow, methane-filled Raman cell has been used for nonlinear conversion of a 100-Hz Nd-YAG laser operating at 1.06 μm to eye-safe radiation at 1.54 μm. The laminar flow is obtained between two concentric cylinders rotating at the same angular velocity. Using a noncritically phase-matched optical parametric oscillator, the same laser source was also converted to 1.57 μm eye-safe radiation. Pump recirculation was used in both cases. Good conversion efficiencies, almost independent of the pulse repetition rate, were obtained with both conversion techniques.

Subject terms: eye-safe; Raman conversion; OPO conversion; high repetition rate.

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1 Introduction

Over the past decade we have been working with a high-repetition-rate scanning lidar system for mapping the density of military and experimental smoke clouds.[1] A high-repetition-rate Nd-YAG laser is used with this system and eye safety has always been a major concern. A study of different nonlinear techniques to produce a viable eye-safe (>1.4 μm), high-repetition-rate laser source was undertaken to reduce the laser safety constraints on our day-to-day operation. Both conversion by stimulated Raman shifting (SRS) and in an optical parametric oscillator (OPO) were experimentally studied and compared at repetition rates of up to 100 pps.

2 Frequency Conversion by SRS in a Laminar Flow Raman Cell

The 1.06-μm radiation produced by a Q-switched Nd-YAG laser can be shifted efficiently to eye-safe radiation at 1.54 μm by SRS in methane. However, thermal blooming effects in the high-pressure SRS medium severely limit the conversion efficiency at a repetition rate higher than 1 to 5 pps unless some gas circulation is used.[2] In our cell this is achieved by a laminar flow entrained by two concentric and corotating aluminum cylinders.[3] A few seconds after the beginning of rotation, the gas between the cylinders has been entrained with them, resulting in a laminar flow. The perturbation caused by both fixed ends is small, the ratio of cell length over the spacing between the cylinders being large (near 30). The angular speed of the cylinders is adjusted to ensure that gas heated by the SRS process in the preceding laser shot has been cleared away. In our case the angular speed was adjusted to approximately 1 Hz.

Figure 1 shows schematically the 28-cm-long laminar flow SRS cell, the lenses used to focus the Nd-YAG laser beam and re-collimate the SRS 1.54-μm pulse, and the SRS resonator that increases and stabilizes the conversion efficiency. The 15.3-cm focal length lens are spaced by 29.4 cm so that the resonator formed by mirrors M1 and M2 is quasi-confocal. Operating pressure was set to 8.3 MPa. In our cell, the outer diameter of the inner cylinder is 6 cm.

Figure 2 shows more details of the three configurations used for the output coupler. Configuration 1 consist of a 10% reflectivity mirror at 1.54 μm so that the pump radiation makes only one pass in the SRS cell. In configurations 2 and 3, a high-reflection coating at 1.06 μm is used to redirect the pump radiation so that it makes a second pass in the active SRS medium. In configuration 2, an independent high-reflectivity mirror at 1.06 μm is used whereas a dichroic coating serves this purpose in configuration 3. A Faraday rotator is used to avoid feedback into the Nd-YAG laser.

The pump of the 1.06-μm Nd-YAG laser operating at up to 100 pps is schematically shown in Fig. 3. It was constructed by the National Optic Institute (NOI).[4] In this polarization-coupled laser, a 2-m convex high reflector is used to compensate for thermal lensing in the Nd-YAG rod. A Taylor prism and a quarter waveplate are used to achieve a 90 deg rotation of the polarization and thus compensate for the birefringent effect in the rod.[5] At 100 Hz, 100 to 120 mJ pulses having a 20 to 25 ns pulse width are obtained. Operation at a lower repetition rate (1, 10, 25, and 50 Hz) is achieved by operating the Q-switch only on the needed shots while the flash lamp is fired at a fixed 100 pps rate. In this manner the pulse shape and spatial quality are well maintained at all repetition rates. The pulse energy could also be varied by changing the charge voltage of the flash lamp power supply.

At 100 pps and at the highest energy, the laser produces a flat-topped multiple transverse mode with a mean power

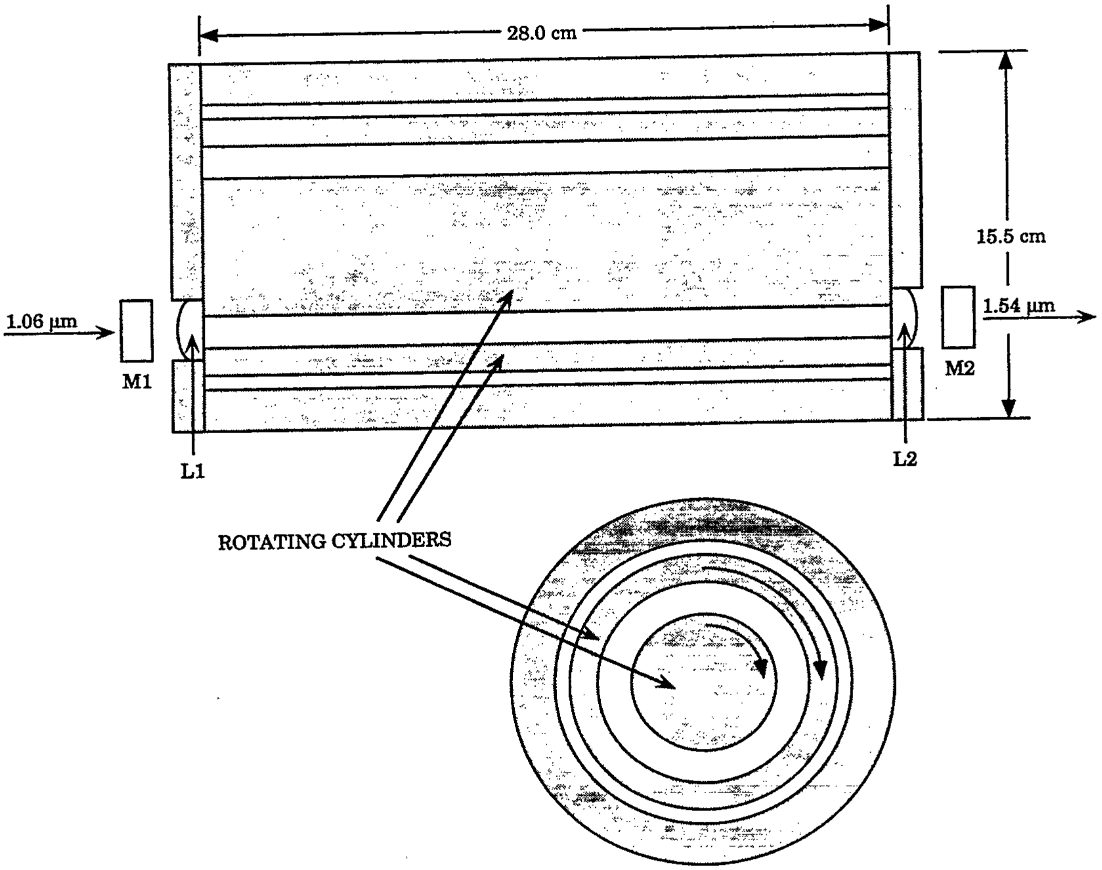


Fig. 1 Laminar flow Raman cell.

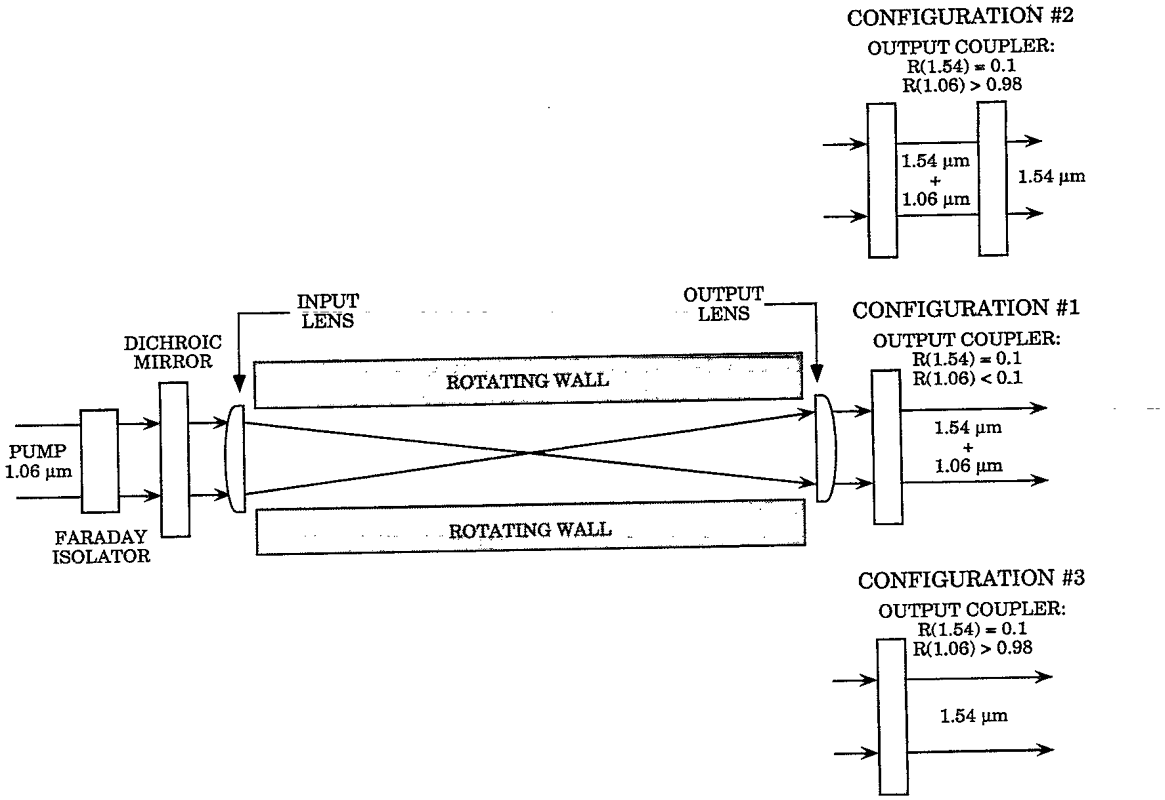


Fig. 2 Laminar flow Raman cell output coupler configurations.

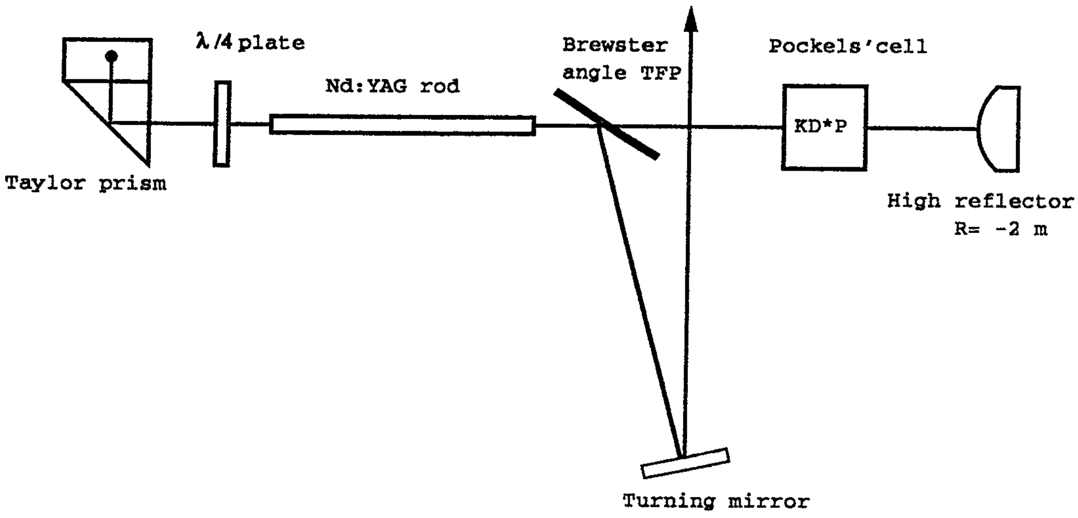


Fig. 3 Schematic diagram of the 100-Hz, 100-mJ Nd-YAG birefringence- compensated laser from NOI.

of up to 12 W. In these conditions, after a few seconds of operation, a decrease in the pulse energy and a concomitant increase in the pulse width are observed. This is further discussed in the following section.

3 Results

Figure 4 shows the variation of the 1.54-μm output energy as a function of the 1.06-μm input energy for the three output coupler configurations. Laser pump refocalization results in a significant decrease in the threshold value and a 20 to 35% increase in energy conversion at the highest (115 mJ) input. The input energy is measured before the Faraday isolator, while the 1.54-μm radiation is measured after a 1.06-μm blocking filter. Figure 5 shows the conversion quantum efficiency, calculated by taking into account the Manley Row conversion efficiency, the pump energy losses in the Faraday isolator, and the transmission at 1.54 μm of the 1.06-μm blocking filter. Energy losses caused by the focusing optic and the laser cavity mirrors are not taken into account. Close to 60% quantum efficiency conversion was obtained with refocalization of the pump beam and the dichroic coupler. Figure 6 shows the 1.54-μm laser pulse shape for configurations 1 and 2 of the output coupler for two input (60 mJ and 110 mJ) energies. It can be observed that the increase in conversion efficiency with configuration 2 results from an earlier onset of conversion and consequently a broadening of the output SRS pulse is observed.

The laser beam divergence (full width 1/e^2), as measured with a 50-cm focal length, is equal to 2.5 mrad. Similar results were obtained at pump repetition rates of 1, 10, 25, and 50 Hz. However, at 100 Hz, two phenomena occur: the Raman output energy is slightly lower than at lower repetition rates during the first few seconds and then it becomes erratic. The lower output is caused by thermal effects from previous laser shots. Simple geometric calculations show that the interaction zones slightly overlap at 100 Hz. The rotation of the gas is slightly too slow. Figure 7 shows the resulting distortion of the laser spot. Changing the direction of the gas flow changes the position of the dip in the laser spot. This phenomenon only occurs at high-energy conversion.

The second phenomenon is an erratic output caused by changes in the output energy of the NOI laser at 100 Hz.

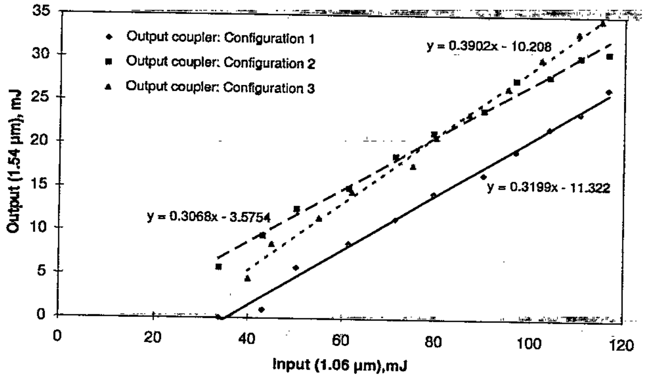


Fig. 4 Dependence of 1.54-μm output energy on the 1.06-μm pumping energy for the three output coupler configurations.

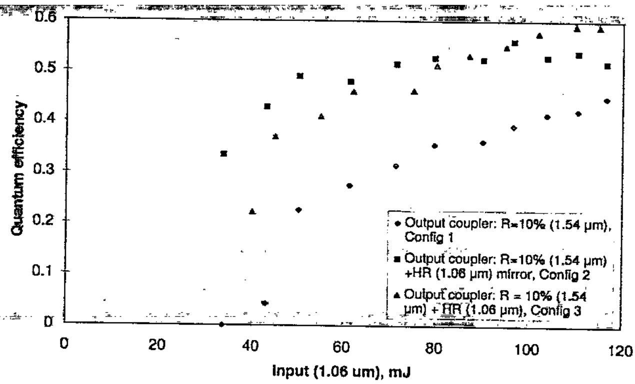
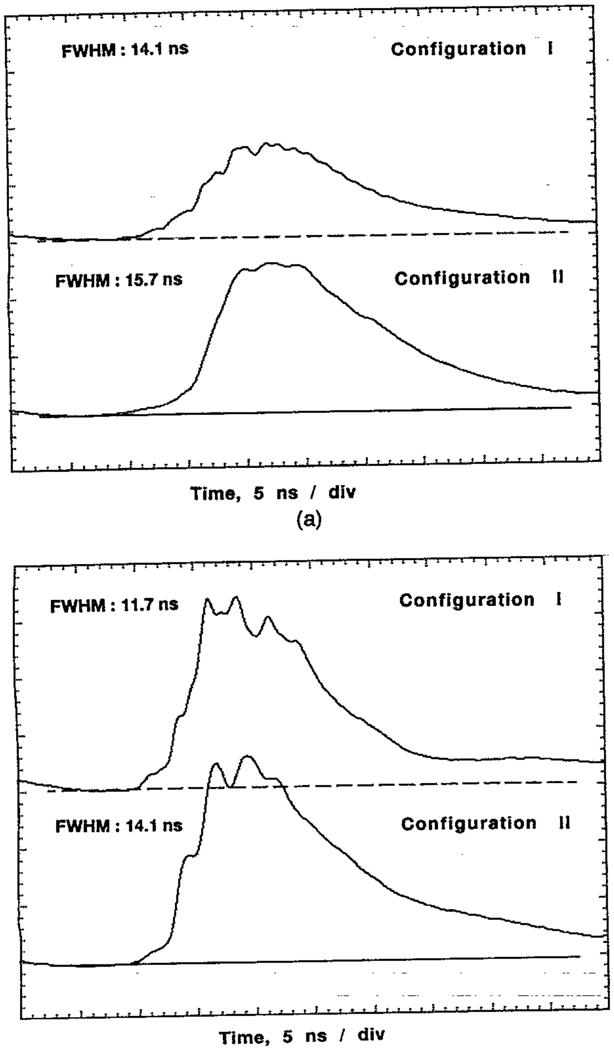


Fig. 5 Dependence of 1.54-μm *conversion efficiency on the 1.06-*μm pumping energy for the three output coupler configurations.



(a)

(b)

Fig. 6 1.54-μm laser pulse shape for output couplers with configurations 1 and 2 for pump laser input of (a) 60 mJ and (b) 110 mJ.

The first laser shots obtained at a repetition rate of 100 Hz have the same amplitude as those obtained at 10 Hz. However, over a few seconds we can observe a gradual decrease in the pulse amplitude and an increase in the pulse width. It appears that heating of the KD*P Q-switch cell degrades the performance of the laser.[6] Therefore after a few seconds, the holdoff decreases and the laser starts to emit some radiation prior to the opening of the Q-switch. This has the effect of increasing the pulse width of the laser and decreasing the oscillating bandwidth. The consequence is an increase in the competition between Raman and Brillouin conversion. Figure 8 shows the competition between these two nonlinear effects as a function of pump energy; output coupler configuration 2 was used. The sudden changes in the outputs are caused by the Q-switch failure at high energy.

4 Frequency Conversion in a KTP OPO

Efficient frequency conversion of 1.06-μm radiation to eye-safe radiation can also be obtained with a KTP crystal in an OPO.[7] Figure 9 illustrates the setup that was used. An X-cut KTP (4 × 4 × 20 mm) crystal gives noncritical phase-matching (NCPM) operation at a measured signal wavelength of 1.573 μm. The idler radiation at 3.28 μm was not observed in this experiment because BK-7 glass mirror substrates having a strong absorption at this wavelength were used. The 3.28 μm radiation is also significantly absorbed in the KTP material. At an energy output of 25 mJ and 100 pps, 1.2 W of 3.28 μm should be generated and absorbed by the OPO mirrors and crystal. There is also some heat generated by the absorption in the KTP at both 1.06 and 1.57 μm.

To reduce the heating effect, the crystal was mounted in an aluminum heat sink with an indium gasket. The crystal was antireflection coated for both 1.06 and 1.57 μm. A 75-cm focal length lens was use to reduce the 6-mm diameter pump beam to approximately 2 mm at the entrance of the OPO. A 50% output coupler was used so that the intracavity 1.57-μm intensity would not exceed the damage

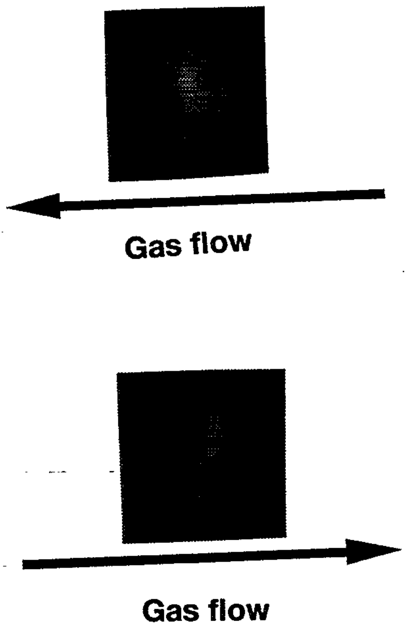


Fig. 7 Effect of slightly insufficient laminar flow speed on SRS beam shape.

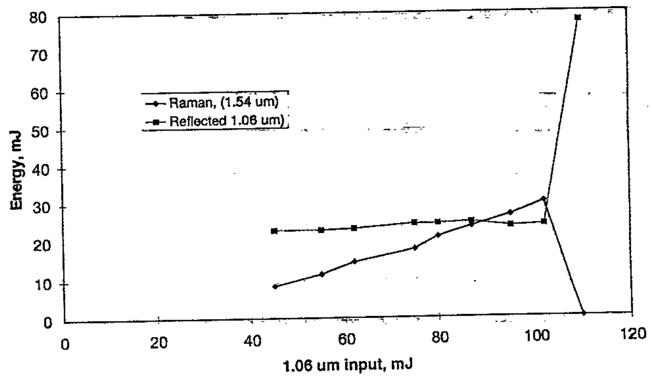


Fig. 8 Competition between Raman and Brillouin conversion.

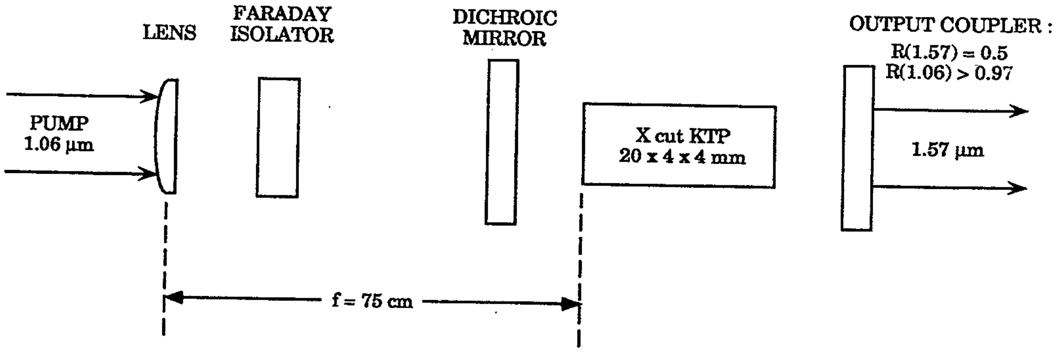


Fig. 9 OPO conversion setup.

threshold of the crystal. This output coupler is also highly (97%) reflective at the pump wavelength. This has the effect of effectively doubling the nonlinear interaction length and consequently significantly reducing the threshold. For an OPO resonator length of 25 mm, the observed threshold was at around 10 mJ. At this energy, the pump laser produces pulses having a full-width half maximum (FWHM) of 50 ns. Thus the OPO has an intensity threshold of approximately 25 MW/cm^2. This compares favorably with other published values.[7,8]

The variation of the OPO output energy at 1.57 μm and conversion efficiency as a function of the 1.06-μm input energy are shown in Fig. 10. The OPO pulse shape compared with the pump pulse shape are shown in Fig. 11 for the same two energy inputs (60 and 110 mJ) as for the SRS conversion. The OPO pulse width is strongly correlated with the pump pulse width. There was virtually no change in conversion efficiency with the repetition rate up to the maximum of 100 pps. However, the antireflection (AR) coating of the entrance face of the KTP crystal was damaged after more than a million pulses at 100 pps and at a pump fluence of about 3.5 J/cm^2. This is substantially lower than the KTP single-pulse damage threshold of 15 to 20 J/cm^2. It must be emphasized that in an OPO, the crystal experiences a much higher peak electric field than that produced by the pump. In fact, superimposed on the pump field, there is also the field from the resonating signal plus a small contribution from the idler. At the entrance of the crystal, on the AR coating, the pump wave is at its maximum. At this point, the signal is a standing wave which, at high conversion efficiencies, can easily have an electric field much higher than that of the pump (especially if the coupler reflectivity is high). It is then necessary to keep the

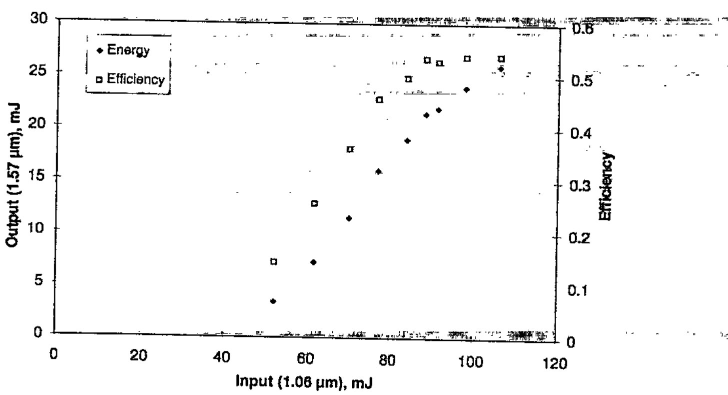


Fig. 10 Dependence of 1.57-μm OPO energy conversion and conversion efficiency on the 1.06-μm pumping energy.

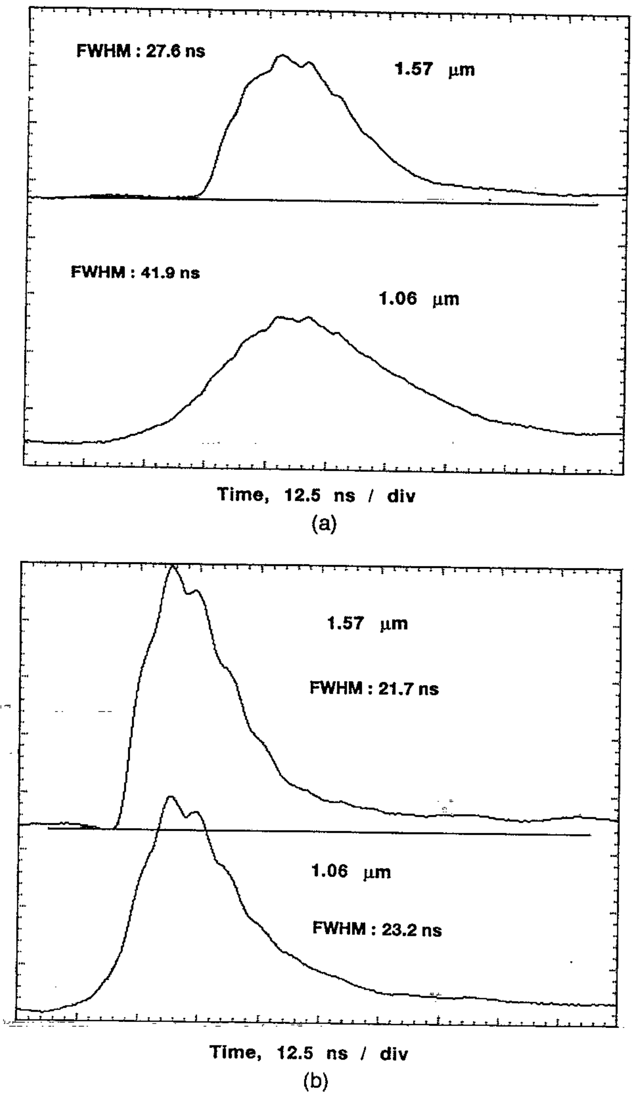


Fig. 11 (a) 1.57-μm laser pulse shape for pump laser input of (a) 60 mJ and (b) 110 mJ.

pump at a fluence much smaller than the damage threshold. As an example, damage in only a few pulses was observed at a pump fluence of 8 J/cm^2 in a similar OPO.[8] Mounting the KTP crystal in a dust-free enclosure is also considered for a future long-term experiment. The laser beam divergence, as measured with a 50-cm focal length, is equal to 2.5 mrad.

5 Discussion and Conclusion

The experimental results demonstrate that eye-safe conversion of a high-repetition-rate (100 pps, 100 mJ) Nd-YAG laser can be achieved both by Raman shifting in a flowing methane cell and by a KTP-based OPO with respective efficiencies of 60 and 50%. The measured beam divergence was 2.5 mrad for both conversion techniques.

The laminar flow Raman cell that was described presents a simple and low-cost design. The gas flow is achieved with a low turbulence, and faster flowing speeds are easy to implement. Operation at higher repetition rates could be obtained with an increase in the diameter of the corotating cylinders. There is always some concern about the safety of the high-pressure methane cell in case of an accidental pressure release. An ample fresh air circulation should always be used.

Conversion by the NCPM KTP OPO does not present this safety problem and it can also be implemented in a much smaller volume. Damage to the AR coating occurs after more than a million shots at high intensity. The use of a lower reflectivity output coupler in the OPO might help resolve this problem. One could also use a larger pump beam. Both methods would likely reduce the conversion efficiency because they will increase the OPO threshold. In all cases the crystal should be maintained in a dust-free environment for long-term operation.

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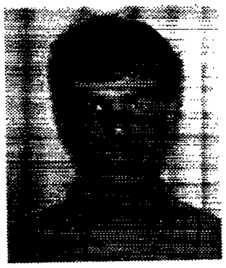
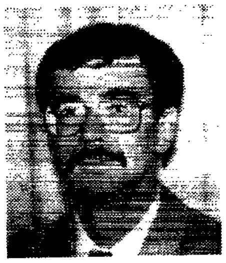


Gilles Roy received his MSc degree in physics from Laval University in 1979. He is currently a research scientist at the Defence Research Establishment Valcartier. His research interests include eye-safe laser sources, multiple scattering, particle sizing and multiple field of view lidar.



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