# LASER SOURCES OF PULSED EYE-SAFE RADIATION

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Pulsed laser sources generating in the eye-safe spectral region (1.4 – 1.8 μm) find a wide application in environmental protection, range finding, active imagining, and in several other areas related to the free-space propagation of laser radiation. At present, there are two main approaches for eye-safe laser developing. The first one consists in direct lasing in this spectral range. Erbium doped glass is a prime candidate for the generation of 1.54-μm eye-safe radiation, especially when codoped with $Yb^{3+}$ ions. However the thermal conductivity of Er-Yb glasses is very low, which is disadvantage to create laser systems with high repetition rates. A great deal of effort has been devoted to the synthesis and research of Er-doped crystals having the much larger thermal conductivity. Nevertheless, practical realization of high average-power laser action in Er-Yb crystals meets a number of obstacles. Among these are the multiphonon 1.5-μm luminescence quenching and the low quantum yield leading to a high lasing threshold.

In view of an imperfection of Er-laser media the second approach based on the nonlinear-optical conversion of the radiation of neodymium lasers by means of stimulated Raman scattering (SRS) and optical parametric oscillator (OPO) is widely used to design eye-safe lasers.

This paper reviews several types of eye-safe laser sources developed by us with the use of the second approach. The results of investigation of their characteristics are reported.

Based upon optical schemes, four kinds of eye-safe sources with nonlinear optical conversion of laser radiation are implemented. In the case of the SRS conversion, so-called self-stimulated Raman lasers in which a single rod is used for both generating and converting the laser radiation are realized. A scheme of such lasers is very simple. It is a two-mirror standing wave cavity including a Nd-doped element and a Q-switch. To obtain the eye-safe radiation, the laser mirrors are coated to achieve a very high Q-factor of the cavity at ~1.34 μm ($^4F_{3/2} - {}^4I_{13/2}$ laser channel of Nd ion) and to provide an output coupler for the 1$^{st}$ Stokes. With the use of an $Nd:KGd(WO_4)_2$ (Nd:KGW) element of 50 mm in length, the natural-air-cooled flashlamp-pumped self-Raman lasers are designed. Lasers provides eye-safe radiation at 1.538 μm. Under active Q-switching ($LiNbO_3$), the pulse width (FWHM) is 3-5 ns depending on the cavity length. At 7-J pumping, the energy of SRS pulse is 14 mJ. The divergence of eye-safe radiation at a level of 86.5 % of the total energy is $\theta_{0.865}$= 6–7 mrad. Under passive Q-switching ($V^{3+}$:YAG), the whole integral SRS-pulse of ~15 ns (rod diameter is ∅=3 mm) or ~25 ns (∅=4 mm) in duration represents an envelope of shorter (~1–2 ns) time-shifted pulses generated by isolated local parts of the cross-section of active medium. The energy of

SRS-radiation is ~9(∅=3 mm) and ~13 mJ(∅=4 mm). The divergence of eye-safe laser beam ($\theta_{0.865}$) does not exceed 12 – 13 mrad.

The diode-end-pumped Q-switched $Nd:YVO_4$ self-Raman laser is designed. The laser emits the 1st Stokes at 1.524 μm. The pulse repetition rate is up to 20 kHz. The average output power of Stokes radiation reaches ~1 W.

The second type of eye-safe sources is based on the extracavity linear Raman lasers driven by a separate multimode Nd:KGW pump laser. When the actively Q-switched flashlamp-pumped pump laser based on ∅4x50 mm Nd:KGW crystal operates at the $^4F_{3/2} – ^4I_{13/2}$ transition (λ=1.351 μm), the eye-safe Raman laser with a double pass of the pump beam emits the 1st Stokes. The extracavity Raman lasers are realized with crystalline $Ba(NO_3)_2$ (eye-safe wavelength is $\lambda_{1St}$= 1.574 μm), a-cut $PbWO_4$ (1.538 μm) and b-cut KGW. In the case of KGW, the source can use either the 767.5- (electrical field vector *E* is parallel $N_g$ crystal axis) or 901.5-$cm^{-1}$ ($E \parallel N_m$) Raman frequency shift and converts laser emission into 1.507- or 1.538-μm eye-safe radiation, respectively. It is also possible to generate eye-safe radiation at both wavelengths simultaneously.

Under extracavity Raman laser, the pump pulse generation and the SRS conversion of laser radiation are independent processes. By virtue of this the FWHM of Stokes pulse approximates to the pump pulse width and is ~20 ns. All Raman lasers provide approximately the same 1st Stokes energy which reaches ~12 mJ at 10 J electrical pump of the source. The divergence of eye-safe beam ($\theta_{0.865}$) does not exceed 11 mrad.

For Nd-laser, traditional $^4F_{3/2} – ^4I_{11/2}$ transition (λ~1.06 μm) has the higher cross section and provides a substantially higher pulsed energy output. However, Raman shift of the frequency of this transition into an eye-safe spectral range requires the generation of higher order Stokes components than in the case of the $^4F_{3/2} – ^4I_{13/2}$ laser channel, since essential Raman frequency shifts of the SRS crystals lie in the range of 700–1100 $cm^{-1}$. We have realized the eye-safe laser source in which the extracavity KGW Raman laser converts the multimode radiation of the Q-switched flashlamp-pumped Nd:KGW pump laser operating at the $^4F_{3/2} – ^4I_{11/2}$ transition into the 3rd Stokes at 1.5 μm ($E \parallel N_m$ geometry of SRS excitation). The optical coatings of Raman laser mirrors ensure the development of a cascade SRS process ending in the 3rd Stokes. At the KGW and Nd:KGW crystals with dimensions such as in the case of the $^4F_{3/2} – ^4I_{13/2}$ transition, Raman laser emitting the 3rd Stokes provides the higher power and energy of the pulse (~ 14.2 mJ) and the smaller divergence of the Stokes beam ($\theta_{0.865}$ ~ 9.4 mrad), besides at the lower pump energy of Nd:KGW laser (~ 6.7 J). In terms of the electrical energy delivered to the flashlamp the total efficiency of the 3rd Stokes Raman laser is ≈ 1.7 times larger. For the 3rd Stokes, the pulse width depends on its energy. When the pulse energy increases from 6 to 14 mJ, the pulse width decreases from 12 to 6 ns. The Raman laser pumped by Nd:YAG with lateral diode pumping is also investigated.

The third type of eye-safe sources is based on the intracavity Raman laser or OPO. The eye-safe source with the intracavity KGW Raman laser which converts the multimode radiation of the pulsed Nd:KGW laser operating on the $^4F_{3/2} - {}^4I_{11/2}$ transition into the 3rd Stokes component at 1.5 μm are realized. The energy in the eye-safe 3rd Stokes is found to increase essentially linearly with the electrical energy delivered to the flashlamp. For the source pump energy of 6 J, the intracavity Raman laser emits 14.7 mJ pulses of duration ~3 ns. The divergence of the Raman laser beam is $\theta_{0.865}$=9 mrad.

The last type of eye-safe sources is based on the extracavity Raman laser or OPO operating in the traveling-wave mode due to ring cavity. The ring cavity is advantageous to design compact laser systems since there is no optical feedback from the nonlinear converter (the optical isolator is not needed). The ring cavity, which consists of three plane mirrors, is used. The optical axial contour of the ring cavity is an equilateral triangle. The ring 1st Stokes KGW Raman laser pumped by mentioned above Nd:KGW laser operating at the $^4F_{3/2} - {}^4I_{13/2}$ transition is realized. The three KGW rods used have the size of ∅2.8 x 22 mm. They are oriented for $N_m$-polarezed pumping ($\lambda_{1St}$=1.538 μm). In ring Raman laser, the presence of the parasitic Stokes radiation generated by the Fresnel reflection back along the path of pump beam leads to the formation of two Stokes waves propagating in opposite directions in the cavity. When eliminating the parasitic Stokes radiation by tilting the ends of the SRS-crystals on 2 - 4 degrees with respect to the cavity axis, the ring Raman laser provides the stable unidirectional generation of the Stokes wave travelling in direction of the pump without any intracavity optical diode. At ~10-J energy supplied to the flashlamp of the pump laser, the ring Raman laser generates 7-mJ, 15-ns pulses with 20 % energy conversion efficiency, the divergence of the Stokes radiation being less than 5 mrad.

Due to the direct conversion of traditional 1-μm emission of the Nd-laser into the eye-safe radiation, the OPO based on KTP (KTiPO4) crystal is an effective alternative to Raman lasers. We have created the eye-safe sources based on a travelling wave KTP-OPO pumped by the flashlamp-pumped water-cooling Q-switched Nd:YAG pump laser generating 9-ns pulses at a repetition rate of 10-12.5 Hz. KTP crystals providing type II non-critical phase synchronism along the *x*-axis ($\theta=90^o$, $\varphi = 0^o$) are used. The length of the KTP crystal is 15 mm. At electrical pumping energy which does not exceed 8 J, the source generates radiation pulses with energy of up to 35 mJ and the duration of ~11 ns.

The output wavelength of the KTP-OPO with pumping by radiation at λ=1.064 μm is 1.571 μm. The long-term operation of the source pumped at 6.5 J is a strong case for its reliability At the continuous operation, the OPO pulse energy has been monitored for more than three-hour intervals that have been separated by an one-hour pause. The average OPO pulse energy of ~25 mJ remains practically constant with a standard deviation of 0.74 mJ. At the output energy of ~25 mJ, the divergence of the OPO beam is less than seven diffraction limits. The fabricated source model with the ring OPO has produced 2.5·million pulses without a substantial change in the characteristics of the output radiation. In some experiments, the Nd:YAG laser with transverse diode pumping is used.

Reasons limiting energy of a ring three-mirror KTP-OPO are revealed. The ways to increase KTP-OPO energy up to ~80 mJ are developed.