09

Electronically wavelength-tuned Cr^{2+}:CdSe laser

© N.G. Zakharov, V.I. Lazarenko, E.V. Saltykov, A.S. Safronov

Lobachevsky University of Nizhny Novgorod, Nizhny Novgorod, Russia
E-mail: dikaion@yandex.ru

Received October 28, 2024
Revised November 7, 2024
Accepted November 7, 2024

We demonstrated acousto-optic and electro-optic wavelength-tuning of Cr^{2+}:CdSe laser with the object of optical monitoring of toxic and inflammable aerosols. In case of acousto-optic wavelength-tuning the frequency of wavelength switching 76 kHz was limited by pump pulse repetition frequency and laser generation linewidth was less than 2 nm. In case of electro-optic tuning the frequency of wavelength switching 36 kHz was limited by Pockels cells relaxation time and laser generation linewidth was less than 0,5 nm. Optical efficiency of laser generation in $\sim 3.3\,\mu$m spectral range was 4% for acousto-optic and 4,5% for electro-optic tuning method.

Keywords: Cr^{2+}:CdSe laser, acousto-optic wavelength-tuning, electro-optic wavelength-tuning, hazardous aerosol detection.

DOI: 10.61011/TPL.2025.03.60718.20172

Laser detection of explosive and toxic aerosols involves measuring the attenuation of two closely spaced spectral lines in the controlled volume, which makes it possible to take into account non-selective losses caused by turbulence and dustiness of the air medium, variations in the scattering coefficient of the underlying surface, etc. Since simultaneous generation of two discrete wavelengths by a single solid-state laser source is usually difficult to implement, and it is impractical to use several sources, the most effective solution is the alternate generation of several spectral lines by a single source. In this case, the switching frequency should be high enough to keep the optical properties of the trace unchanged in the interval between two measurements.

For Cr^{2+}:ZnSe-laser, a method of acousto-optic spectrum control was implemented, which involves placing an acousto-optic filter based on paratellurite [1] in the laser resonator. The above method allowed tuning the laser emission in the spectral range from 2.17 to 2.71 μm with a switching frequency of the emission wavelength of 10 Hz. The emission line widths ranged from 50 to 100 GHz, i.e., 1 to 2 nm, for the $\sim 2.5\,\mu$m wavelength.

Also for Cr^{2+}:ZnSe- and Cr^{2+}:ZnS-lasers, a spectrum control method consisting in leveling the standing optical wave in the active medium by placing two quarter-wave [2] plates in the resonant cavity was implemented. In the continuous emission mode, the above method was able to generate a single discrete line in the spectral region$\sim 2.4\,\mu$m for Cr^{2+}:ZnSe and $\sim 2.3\,\mu$m for Cr^{2+}:ZnS. The emission width did not exceed 80 pm, which corresponded to the resolution limit of the instrument used.

This paper describes an Cr^{2+}:CdSe-laser with the possibility of rapid tuning of the emission wavelength for the optical detection of flammable and toxic aerosols with characteristic signatures in the $\sim 3.3\,\mu$m spectral region. Two options of the laser source are implemented i.e. the one with acousto-optical and electro-optical spectrum switching method.

Optical scheme of the Cr^{2+}:CdSe-laser is shown in Fig. 1. A tulium fiber laser was used as a pump source *1*, generating radiation pulses with wavelength $\sim 1.908\,\mu$m, pulse duration ~ 182 ns, pulse repetition rate ~ 76 kHz and maximum radiation power ~ 20 W. The pump radiation was focused using a lens *2* with a focal length of ~ 250 mm into the active element *4*. The diameter of the pump radiation beam in the active element was ~ 0.3 mm. The active element was an Cr^{2+}:CdSe ~ 4.5 mm-long crystal grown from the vapor phase. The crystal had polished and anti-reflection coated end faces. The active medium was moved perpendicular to the axis of the resonant cavity with a velocity of ~ 28 m/s.

The resonant cavity was formed by flat mirrors: a end mirror *7* with a high reflection coefficient in the generation region, an output mirror *9* with a reflection coefficient in the generation region of ~ 90 % and two deflecting mirrors *3* and *6* with a high reflectance coefficient for the generation radiation and transparent for the pump radiation. Focusing lenses *5* and *8* were placed in the resonant cavity to match the pump and generation modes.

In order to determine the relative energy efficiency of the methods used, a scheme with wavelength tuning of the radiation into the $\sim 3.3\,\mu$m spectral range was implemented using a spectral filter *10F* placed in the resonant cavity. When the acousto-optic method was used, an acousto-optic filter *10A* based on a paratellurite crystal with a diffraction efficiency of ~ 97 % was installed in place of the spectral filter. When the electro-optical method was used, a ZnSe *10E* wafer placed at the Brewster angle was installed in place of the spectral filter, and Pockels *11E* and *12E* cells based on lithium niobate crystals were also placed in the resonant cavity.

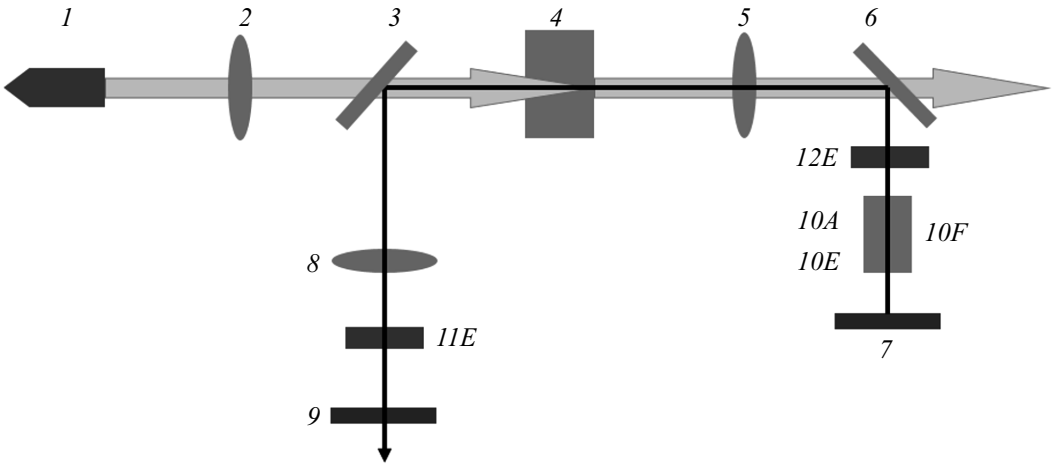

Figure 1. Optical scheme of the Cr^{2+}:CdSe-laser. See the explanation in the text.

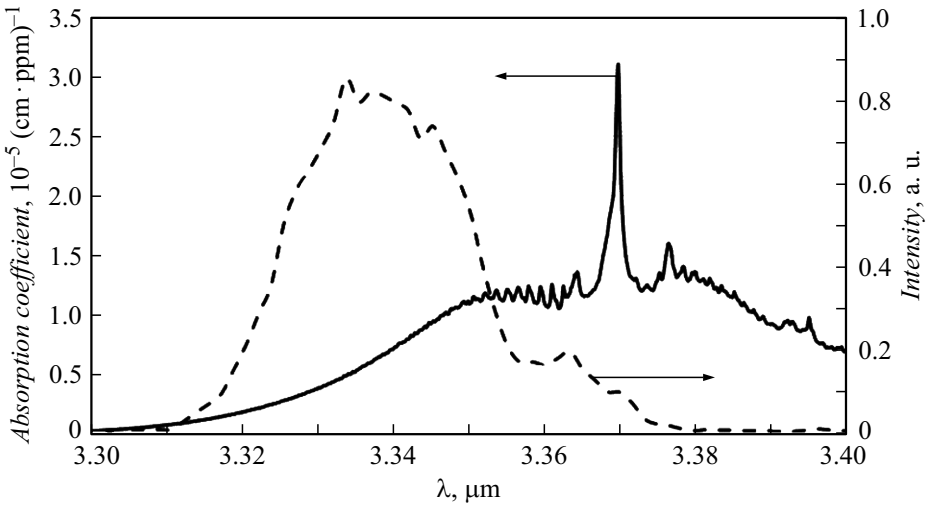

Figure 2. The generation spectrum of Cr^{2+}:CdSe with an intracavity spectral filter (dashed line) and the absorption coefficient of the propane mixture (solid line).

A laser source with an intracavity spectral filter generated radiation in the $\sim 3.35\,\mu$m spectral region with an optical efficiency of $\sim 4.3\,\%$. The spectral width of the emission was ~ 70 nm to the base. The radiation adjustment in the range from 3.3 to $3.4\,\mu$m was done by mechanical rotation of the filter. The filter was an interference-coated wafer whose rotation resulted in a spectral shift of the transmission maximum by changing the effective thickness of the interference layers. The generation spectrum of Cr^{2+}:CdSe with an intracavity spectral filter is shown in Fig. 2. The figure also shows the dependence of the absorption coefficient of the propane mixture widely used in fuel systems on the wavelength of radiation presented in the HITRAN spectral database.

Laser sources with acousto-optic and electro-optic spectrum control alternately generated radiation at two wavelengths by alternating the amplitudes of the control signals. During the generation of the first pulse, a constant frequency signal ~ 30.12 MHz, was applied to the acousto-optic filter and a constant voltage ~ 4.96 kV, was applied to the Pockels cells, experimentally selected by magnitude so that the sources generated radiation with wavelength $\sim 3.31\,\mu$m. During the generation of the second pulse, a constant frequency signal ~ 29.72 MHz, was applied to the acousto-optic filter and a constant voltage ~ 5.03 kV was applied to the Pockels cells, experimentally selected in magnitude so that the sources generated radiation with wavelength $\sim 3.35\,\mu$m was applied to the Pockels cells. The cycle was then repeated.

For the acousto-optic method, the maximum switching frequency between the two spectral lines is limited by the transit time of the sound wave through the radiation beam. Since the diameter of the generation radiation in the region of the acousto-optic filter location did not exceed 1 mm, and the speed of sound in paratellurite is ~ 850 m/s, the maximum switching frequency could reach ~ 850 kHz.

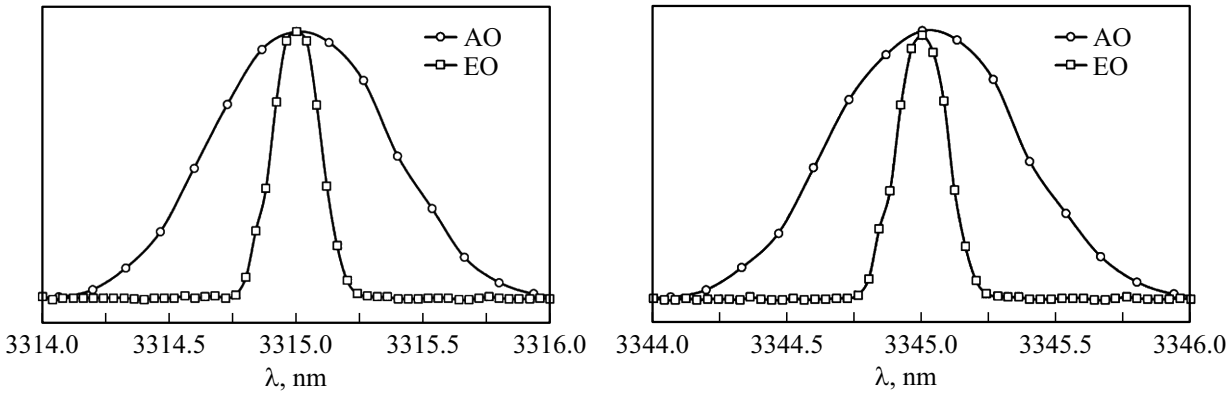

Figure 3. Generation line spectra at acousto-optical (AO) and electro-optical (EO) spectrum control in the ~ 3.31 and $\sim 3.35\,\mu$m regions.

In our case, the switching frequency was limited by the repetition rate of the pump pulses. Thus, for the acousto-optic method, the switching frequency between the two wavelengths was ~ 76 kHz.

For the electro-optical method, the maximum switching frequency was limited by the relaxation time of the piezoelectric stresses in the Pockels cells. Since, according to experimental data, the total relaxation time of the used Pockels cells did not exceed $\sim 25\,\mu$s, only every second pumping pulse was applied to the active element. Thus, for the electro-optical method, the switching frequency between the two wavelengths reached the value ~ 38 kHz.

For both methods, the switching between the spectral lines was confirmed using a diffraction grating and two fast photodiodes.

The spectra of the generation lines under acousto-optic and electro-optic spectrum control in the~ 3.31 and $\sim 3.35\,\mu$m regions are shown in Fig. 3. As can be seen from the figure, the spectral width of the emission in the case of the acousto-optic method was ~ 2 nm to the base, which corresponded to the spectral resolution of the acousto-optic filter used. In the case of the electro-optical method, the spectral width did not exceed ~ 0.5 nm to the base, which corresponded to the resolution of the device used.

The true spectral width of the generation line in the case of the electro-optical switching method is quite difficult to determine. If in the case of the acousto-optic method a spectral filter is simply introduced into the resonant cavity (in our case radiation with a wavelength and polarization not satisfying the Bragg diffraction conditions was deflected by the angle $\sim 7^\circ$ from the resonant cavity axis), the electro-optic method radically changes the character of laser generation. If a quarter-wave voltage is applied to the Pockels cells, the generation radiation has different polarization in different parts of the resonant cavity. Between the end mirror *7* and cell *12E*, the radiation has linear polarization, the direction of which is determined by the orientation of the wafer *10E*. Between the cells *12E* and *11E*, the radiation has circular polarization. Between the *11E* cell and the output mirror *9*, the polarization of radiation is linear. The polarization directions in the two outermost segments of the resonator are oriented perpendicularly with respect to each other.

Since the generation radiation passing through the active element *4* has circular polarization, there is no standing optical wave with alternating minima and maxima of intensity in the active medium and, consequently, the effect of the so-called „hole burning“, leading to the simultaneous coexistence of multiple longitudinal modes of radiation [2], is eliminated. Thus, under conditions of absolute stability such a source should generate radiation on a single longitudinal mode for which the resonant cavity bypass loss is minimal. However, since the polarization losses at deviation of the radiation wavelength from the wavelength corresponding to the quarter-wave voltage increase very slightly, there is actually a constant switching of generation between neighboring longitudinal modes, i.e., the radiation spectrum in this case is not single-mode, which could be detected by interferometric methods, but at the same time is too narrow to determine its width by standard spectral devices. Nevertheless, for the task of optical detection of aerosols with a smooth dependence of the absorption coefficient on the radiation wavelength, the uncertainty of the spectral width of the order of fractions of a nanometer is quite acceptable.

Energy-wise, laser sources with electro-optic and acousto-optic spectrum switching methods were comparable to a spectral filter-based source. The source with the electro-optical method generated radiation in the spectral region $\sim 3.3\,\mu$m with an optical efficiency of $\sim 4.5\,\%$. The source with the acousto-optical method generated radiation in the spectral region $\sim 3.3\,\mu$m with optical efficiency $\sim 4\,\%$.

Thus, laser sources based on polycrystal Cr^{2+}:CdSe were created for optical monitoring of explosive and poisonous aerosols. They allow alternately generating radiation at two wavelengths in the $\sim 3.3\,\mu$m spectral region, which is not available for widespread Cr^{2+}:ZnSe-lasers. For the source with the acousto-optical method of spectrum switching the

switching frequency was 76 kHz at the spectral width of the generation lines ~ 2 nm. For the source with the electro-optical spectrum switching method, the switching frequency was 38 kHz with the spectral width of the generation lines not exceeding 0.5 nm.

The generation wavelengths were selected so that one of them had a low and the other a high absorption coefficient in the explosive propane mixture. By changing the frequency of the acoustic signal or the voltage applied to the Pockels cells, the generation lines can be reconfigured to match the characteristic signature of one of the toxic aerosols of the BTEX group (benzene, toluene, ethylbenzene, xylene), which have strong absorption bands in the spectral region$\sim 3.3\,\mu$m [3].

Moreover, the implemented switching frequencies basically allow scanning the spectral region $\sim 3.3\,\mu$m with the frequency ~ 1 kHz, i.e., obtaining information on absorption in the air medium not for two, but for several tens of different spectral lines. Such information can be used for detection of any mixture of toxic and explosive aerosols in the air medium.

Funding

The study was supported by the national project „Science and Universities“ (project FSWR-2024-0004) funded by the Federal Budget subsidy for financial support of state order for research and development works.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M. Yumoto, N. Saito, U. Takagi, Opt. Express, **23** (19), 25009 (2015). DOI: 10.1364/OE.23.025009
[2] R. Danilin, V. Fedorov, D. Martyshkin, O. Gafarov, S. Mirov, Opt. Express, **31** (8), 12686 (2023). DOI: 10.1364/OE.486474
[3] M.M.Y.R. Riad, Y.M. Sabry, D. Khalil, in *2019 36th National Radio Science Conf.* (NRSC) (IEEE, 2019), p. 386. DOI: 10.1109/NRSC.2019.8734644

Translated by J.Savelyeva