Multiwavelength mid-IR spatially-dispersive CW laser based on polycrystalline Cr^{2+}:ZnSe

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Abstract: For the first time we demonstrate a multiwavelength, ultrabroadband, continuous-wave, tunable, polycrystalline Cr^{2+}:ZnSe spatially-dispersive laser, operating in the near IR spectral region. We show a dual-wavelength operation of the laser, tunable over a 600 nm spectral range (2200-2800 nm), an ultrabroadband operation of the laser, producing a continuous 135 nm wide spectrum centered at 2500 nm, and show a 200 nm wide (2400–2600 nm) multiline, tunable output spectra, consisting of up to 40 spectral lines. We also show simultaneous tuning of a 20–lines ultrabroadband spectrum over a spectral range of 2200–2800 nm.

OCIS codes: (140.3580) Lasers, solid-state; (140.3600) Lasers, tunable; (140.3070) Infrared and far-infrared lasers; (140.5680) Rare-earth and transition-metal solid-state lasers;

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1. Introduction

Multiwavelength spectroscopy, free-space optical communications, optical coherence tomography, and numerous wavelength specific military applications stimulate growing demand for room-temperature mid-IR sources of radiation, combining variable spatial coherence with continuous ultrabroadband or multiwavelength spectrum. Since the pioneering research works of DeLoach *et al.* [1] and Page *et al.* [2] on detailed investigation of the spectral properties of metal-doped zinc chalcogenides, continuous-wave, gain-switch and mode-locked lasing of Cr^{2+}:ZnS and Cr^{2+}:ZnSe were demonstrated [3–7]. Earlier we reported on efficient room-temperature continuous-wave (cw), gain-switched and mode-locked lasing of chromium-doped mono- and polycrystals, prepared by the after-growth thermal diffusion method, in selective and non-selective, microchip- and external cavity configurations, operating over a spectral range of 2200–2900 nm [8]. Recently we also presented an 1.85 μm laser diode pumped, polycrystalline Cr^{2+}:ZnSe laser system, operating at 2460 nm [9]. In this work we demonstrate a new multiwavelength, ultrabroadband, continuous-wave, widely tunable, polycrystalline Cr^{2+}:ZnSe laser based on a Littrow-mounted grating spatially-dispersive cavity. The key feature of this laser is its capability of generating a large number of cw spectral lines simultaneously, with the overall spectral width of the output radiation of several hundred nanometers. This effect is achieved by an efficient suppression of the intracavity mode competition by means of the spatial separation of different frequency components of the laser radiation in the gain medium, so that each lasing frequency is amplified inside its own region of the gain medium independently of the other frequencies [10–13]. In the Littrow-mounted grating spatially-dispersive laser the spectral control of the output radiation is achieved via manipulation of the spatial distribution of the pump radiation in the gain medium [14].

First, we present a dual-wavelength operation of the spatially-dispersive laser, tunable over a 600 nm spectral range (2200–2800 nm). We show how the output spectral lines can be tuned simultaneously or individually by means of the transverse motion of the pump beams across the laser crystal. Second, we show an ultrabroadband operation of the laser, pumped with a highly elliptical, horizontally stretched laser beam. The laser produces a wide continuous spectrum with the overall spectral bandwidth of up to 135 nm (which was mainly limited by the available pump power and the intracavity losses) centered around 2.5 μm. Third, we demonstrate a 200 nm wide (2400–2600 nm) multiwavelength output spectrum consisting of a large number of spectral lines (up to 50), obtained from the ultrabroadband spectrum by means of a self-formed intracavity interferometer. In this case the number of spectral lines and the wavelength spacing can be continuously changed by tuning the interferometer free spectral range. Finally, we show a tuning of a 200 nm wide multiwavelength (20–lines) spectrum over a 600 nm spectral range (2200–2800 nm) by rotation of the Littrow-mounted grating in its dispersion plane.

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2. Experimental setup

A detailed theoretical and experimental analysis of the spatially-dispersive laser can be found in our previous publications [14, 15]. Here we will only briefly outline its principle of operation. The schematic diagrams of the spatially-dispersive laser cavities and the pumping systems, used in these experiments, are shown in Fig. 1. The figure shows the dual-wavelength and the multiwavelength ultrabroadband lasers.

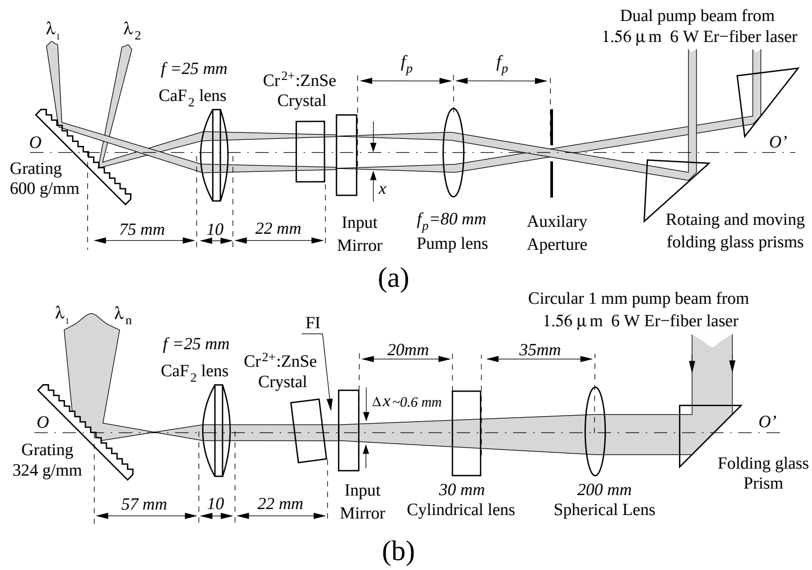

Fig. 1. Schematic diagrams of the dual-wavelength spatially-dispersive laser pumped by a dual pump beam (a), and the multiwavelength ultrabroadband spatially-dispersive laser pumped by a highly elliptical, horizontally stretched pump beam (b). The beam cross section in the latter case is approximately $600 \times 50\,\mu\text{m}^2$.

The laser cavity consists of four major elements: a broadband plane input mirror (with a dichroic coating providing 99.9% and 0.1% transmissions for 1.56 μm and 2150–2850 nm, respectively), a laser crystal ($4 \times 8 \times 1$ mm^3 (l×w×h), uncoated polycrystalline Cr^{2+}:ZnSe with the chromium concentration of approximately 2×10^{19} cm^{-3}), an intracavity focusing lens (25 mm, uncoated CaF_2 lens) and a diffraction grating, installed in the Littrow mount configuration (Au-coated, 2500 nm blaze wavelength, 98% reflection into the 1st order of diffraction). The intracavity lens and the diffraction grating provide a spatial dispersion of different frequency components of the laser gain profile in the active medium, thus enforcing each frequency to be amplified in its own region of the laser crystal. As a result, the mode competition, natural for conventional lasers, is eliminated and the laser operates at many wavelengths simultaneously.

In the dual-wavelength laser, depicted in Fig. 1(a), the pump radiation is split into two beams and each of them pumps its own region of the laser crystal. The transverse positions of the beams in the gain element, together with the parameters of the intracavity lens and the diffraction grating, determine the lasing wavelengths. The pump beams can be gradually shifted in the transverse direction, at the same time remaining parallel to each other and focused into the crystal, which is done by the horizontal rotation and motion of the folding prisms (the auxiliary aperture is used to indicate the front focal point of the pump lens). Due to a combined operation of the intracavity lens and the Littrow-mounted grating, a fraction of the gain medium located

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at a distance x from the optical axis (see Fig. 1(a)) amplifies only one wavelength λ determined by the following expression:

$$\lambda(x) = \lambda_0 - \frac{x}{f}(4t^2 - \lambda_0^2)^{\frac{1}{2}} = \lambda_0 - 2t\frac{x}{f}\cos(\beta), \tag{1}$$

where t–is the grating spacing constant, f–focal length of the intracavity length, β–angle between the optical axis OO' and the grating normal, λ_0–the central wavelength, i.e., the wavelength that would be generated in the axial region of the gain element. Therefore, tuning the output spectrum can easily be done by changing the transverse positions of the pump beams. Moreover, the spectral distribution of the output radiation can be controlled by the spatial distribution of the pump radiation in the gain element.

In the ultrabroadband mode of operation, a wide fraction of the laser crystal is pumped by a highly elliptical, horizontally stretched pump beam (which is equivalent to pumping the laser with a large number of separate overlapping pump beams), as shown in Fig. 1(b), and different wavelengths are amplified in the regions of the crystal located at different transverse distances x from the optical axis. Such a spatially-dispersive amplification gives rise to the generation of a broad continuous output spectrum, consisting of a large number of close spectral lines. The overall output spectral bandwidth $\Delta\lambda$ in this case is given by the following expression, derived from (1):

$$\Delta\lambda = \frac{\Delta x}{f}(4t^2 - \lambda_0^2)^{\frac{1}{2}} = \Delta x\frac{2t}{f}\cos(\beta), \tag{2}$$

where Δx is the total width of the pumped region, as shown in Fig. 1(b). It should be noted that Eqs. (1) and (2) are valid only in the paraxial approximation, i.e. when $x/f \ll 1$ (see [15] for details). The pump system of the ultrabroadband laser consists of two lenses: a long focal length spherical lens, that is used to adjust the width of the pump beam inside the Cr^{2+}:ZnSe crystal, and a short focal length cylindrical lens for compressing the pump beam in the vertical plane, to achieve the threshold intensity of the pump radiation.

The laser crystal and the intracavity lens were not AR-coated for the lasing wavelengths, causing large intracavity losses. Indeed, the Fresnel reflections at two surfaces of the laser crystal ($n = 2.44$ at 2.6 μm) and on the surfaces of the intracavity lens ($n = 1.42$ at 2.6 μm) give a single-pass loss of about 40%. This results in a small output power (up to approximately 15 mW), despite the high pump power (the maximum incident pump power was about 6 W, and the absorption of the Cr^{2+}:ZnSe crystal was 70% at 1.56 μm). It is clear that in these conditions the output power could not be optimized and our work was concentrated on the investigation of the spectral properties of the polycrystalline Cr:$^{2+}$ZnSe spatially-dispersive laser. However, we believe that with the AR-coated laser crystal and the intracavity lens one can expect the slope efficiency of more than 50% [8].

Although in the present configurations the laser works well above the lasing threshold, the intracavity losses reduce the overall bandwidth of the ultrabroadband output spectrum. Another consequence of the absence of the AR coatings is that the uncoated input facet of the laser crystal, together with the working surface of the plane input mirror, forms an intracavity interferometer, which modulates the ultrabroadband output spectrum. When the crystal is almost parallel to the input mirror surface and is located very close to it, such spectrum modulation is irregular and causes some non-smoothness of the ultrabroadband output spectrum. However, if the crystal is tilted in the horizontal plane to form a slightly wedged air gap between the uncoated input facet of the crystal and the reflecting surface of the input mirror, a tunable intracavity Fizeau interferometer (denoted as “FI” in Fig. 1(b)) is created and a regularly spaced discrete multiwavelength output spectrum is observed. The longitudinal position of the laser crystal determines the interferometer free spectral range, whose variation results in a gradual tuning of the wavelength spacing between the output spectral lines.

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3. Experimental results

The output spectra of the dual-wavelength laser (Fig. 1(a)) and the separate tuning of the output spectral lines are shown in Fig. 2. In this case each wavelength is tuned individually by changing the transverse distance between the pump beams, so that the wavelength separation is gradually changed from 73 to 560 nm.

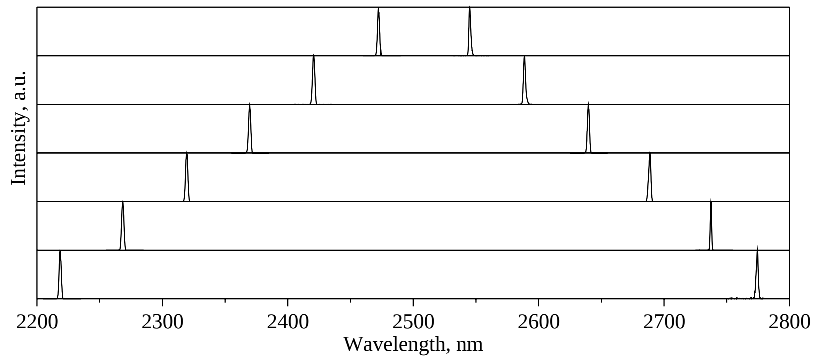

Fig. 2. Individual tuning of the dual-wavelength output by changing the spatial separation between the pump beams.

The simultaneous tuning of the output wavelengths is shown in Fig. 3, where two wavelengths, separated by approximately 50 nm, are tuned over a 600 nm spectral range by transverse motion of the entire dual pump beam across the Cr^{2+}:ZnSe crystal. The spectral tuning range is mainly limited by the spectral bandwidth of the input mirror (2150–2850 nm). Exactly the same tuning of the dual-wavelength spectrum, as shown in Fig. 3, was also performed by rotation of the diffraction grating in its dispersion plane.

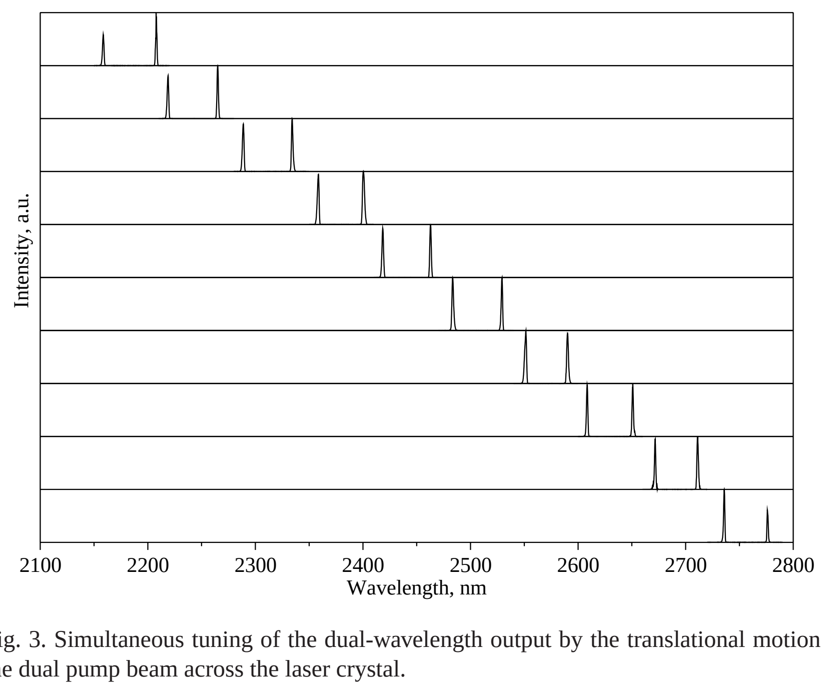

Fig. 3. Simultaneous tuning of the dual-wavelength output by the translational motion of the dual pump beam across the laser crystal.

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The examples of the output spectra of the ultrabroadband laser (Fig. 1(b)) are shown in Fig. 4. These spectra correspond to slightly different angular adjustments of the laser crystal in the vertical plane. The irregular modulation of the ultrabroadband spectra results from an interference of the laser radiation in the air gap between the crystal and the mirror, as explained in the previous section. With the AR coating on the input facet of the laser crystal the interference would be eliminated, and the ultrabroadband spectrum would have a smooth, continuous shape corresponding to the intensity distribution of the pump beam.

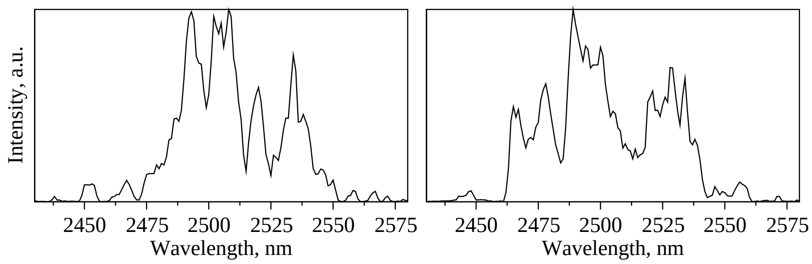

Fig. 4. Ultrabroadband, quasi-continuous output spectra.

The multiwavelength ultrabroadband spectra are shown in Fig. 5, where the wavelength separation is tuned by the intracavity interferometer: as the free spectral range of the interferometer is decreased, the number of output wavelengths increases (and the wavelength spacing decreases), eventually leading to a quasi-continuous output spectrum.

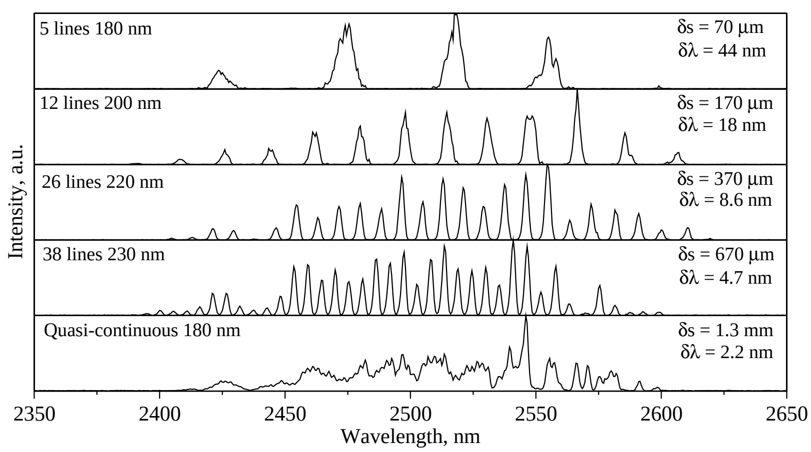

Fig. 5. Tunable multiwavelength ultrabroadband output spectra.

In this tuning experiment the separation between the laser crystal and the input mirror (indicated in the graphs of Fig. 5 as δs) was changed from approximately 70 μm to 1.3 mm, changing the interferometer free spectral range (indicated in the figure as $\delta\lambda$) from 44 nm to 2.2 nm. The finesse of the interferometer, estimated from the reflection coefficients of the input mirror (99.9%) and the input facet of the crystal (17.5%), is about 3.5. Thus, when the crystal is located at a distance of less than 8 μm from the mirror, the interferometer bandwidth is about 130 nm and the entire ultrabroadband spectrum is located within a single transmission peak of the interferometer, which is what happens with the spectra shown in Fig. 4. Such an interferometric method of modulation and tuning of the ultrabroadband spectrum can be used

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for obtaining a discrete multiwavelength spectrum as an alternative to the multi-beam pumping, as in the dual wavelength laser, and to the use of a spatial mask, as was done in the case of the LiF:F_2^- and LiF:F_2^+ lasers described in work [14].

It is also possible to perform a tuning of the entire multiwavelength spectrum by means of rotation of the diffraction grating in its dispersion plane. Such a tuning is depicted in Fig. 6, where approximately 20-line, 200 nm broad spectrum is tuned over a 600 nm spectral range.

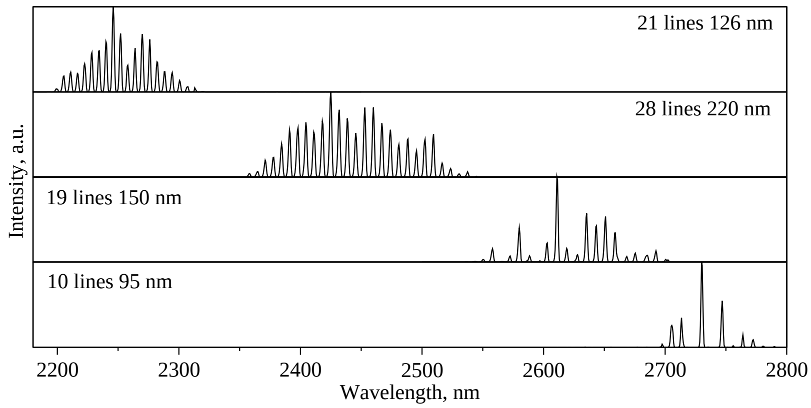

Fig. 6. Tuning of the entire multiwavelength ultrabroadband spectrum by rotation of the cavity diffraction grating in its dispersion plane.

Note, that in the spectral region of approximately 2550–2800 nm some spectral lines are suppressed by the intracavity atmospheric water absorption. This effect, generally undesirable, opens an interesting possibility of creating a sensitive intracavity laser gas sensor for detecting low concentrations of gases. For that purpose it is necessary to build the spatially-dispersive laser that produces a continuous ultrabroadband output spectrum that has the shape of the top-hat function. This can easily be done by proper shaping of the wide pump beam to compensate for the non-constant gain curve of the laser material. Then, a gas flow cell should be installed in the cavity at the focal point of the intracavity lens, where all wavelength channels intersect with each other. The positions and the strength of the distortions of the output spectrum due to the absorption of the flowing gases will allow their identification [16].

4. Conclusion

In this paper for the first time we demonstrate a multiwavelength, ultrabroadband, continuous-wave, broadly tunable mid-IR (2200–2800 nm) laser source, based on 1.55 μm Er-fiber-laser pumped, polycrystalline Cr^{2+}:ZnSe gain medium, utilized in a Littrow-mounted grating spatially-dispersive cavity. We show that the spatially-dispersive laser can operate at many wavelengths simultaneously, producing a tunable discrete multiwavelength output spectrum as well as a continuous ultrabroadband spectrum. We also demonstrate several different methods for tuning the laser output spectrum: by changing the spatial distribution of the pump radiation in the gain medium, by rotation of the Littrow-mounted diffraction grating, and by tuning a self-formed intracavity interferometer. We experimentally demonstrate feasibility and applicability of the Littrow-mounted grating spatially-dispersive laser, based on the polycrystalline Cr^{2+}:ZnSe, for generation of multiwavelength, ultrabroadband laser radiation in the middle infrared spectral region.