Ultrabroad Mid-Infrared Tunable Cr:ZnSe Channel Waveguide Laser

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***Abstract*—Operation of a Cr:ZnSe external-cavity waveguide laser is demonstrated with a CW tuning range of 700 nm from 2077–2777 nm (700 nm or 36 THz), the widest tuning range demonstrated by a waveguide laser. Narrow linewidths as low as 53 pm FWHM (3 GHz) are achieved and a maximum output power of 120 mW is attained at 2446 nm with over 15 mW available across the entire tunable range. A theoretical model is presented allowing the effect of changes to the system to be quantified in terms of laser performance; this allows the limitations of the architecture to be assessed. Good agreement is seen between the model and the experimental values obtained.**

***Index Terms*—Channel waveguide lasers, mid-infrared lasers, transition metal solid-state lasers, ultrafast laser inscription.**

I. Introduction

MID-INFRARED laser sources in the 2–5 μm region are essential for a wide range of scientific, medical and military applications. The location of fundamental and overtone vibrational absorption lines of many organic and inorganic molecules in this spectral region may be exploited for technologies such as remote sensing, breath analysis and laser surgery [1]–[3]. Such technologies require the development of high power, widely tunable, narrow linewidth sources capable of operation at room temperature within this mid-infrared wavelength range. Currently, these applications predominantly employ quantum cascade lasers [1], with both pulsed and CW outputs having demonstrated successful gas sensing [4], [5]. However, the availability of quantum cascade lasers (QCL) in the 2–3.5 μm region is limited by material limitations such as conduction band offset [6], [7]. Consequently, the combination of key criteria such as room temperature operation, wide tunability and high average power operation is not easily realized using QCL technology. Transition metal doped II–VI semiconductor lasers have been shown to meet all these criteria with Cr:ZnSe in particular demonstrating room temperature operation with single longitudinal mode output [8], wide tunability of 1973–3349 nm [9], and high power CW and pulsed operation of 14 [10], and 18.5 W [11], respectively. The maturity of these laser materials has led to the availability of both high power and widely tunable commercial Cr:ZnSe and Cr:ZnS systems [12]. Recent development of Cr:ZnSe waveguide laser sources [13]–[15], has opened the door to the development of compact, environmentally robust mid-infrared lasers suitable for applications outside of the laboratory, with output power up to 1.7 W [16]. In this paper we demonstrate the successful operation of an external-cavity waveguide laser fabricated in Cr:ZnSe with narrow linewidth output in the 2–3 μm region which shows the potential for integration with existing high power diode lasers to create compact [17], broadly tunable and environmentally stable sources. Initial results were presented in mid-infrared coherent sources [18].

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II. Waveguide Fabrication

Waveguides were fabricated through ultrafast laser inscription (ULI) [19], [20] in a $8.5 \times 6.5 \times 2.1$ mm polycrystalline Cr:ZnSe sample doped to a concentration of 8.5×10^{18} cm^{-3}. ULI relies on the nonlinear absorption of tightly focused ultrashort pulses beneath the surface of a transparent dielectric material. The high irradiances generated at the focus of the inscription beam allow nonlinear absorption of the radiation resulting in a transfer of energy to the material lattice. This energy transfer may result in a localized material refractive index change which, when carefully controlled, can be utilized to directly inscribe subsurface channel waveguide structures. The inscription laser (IMRA μJewel D400) provided 750 fs pulses at a repetition rate of 100 kHz with pulse energies of 2.5 μJ at 1047 nm. The waveguide structures consisted of an annular arrangement of individual modification elements, similar to structures first demonstrated in Nd:YAG by Okhrimchuk *et al.* [21], which have recently been extended to Cr:ZnSe substrates achieving low-loss mid-infrared waveguides [14].

The inscription beam was focused using a 0.6 NA aspheric lens and the sample was translated through the inscription

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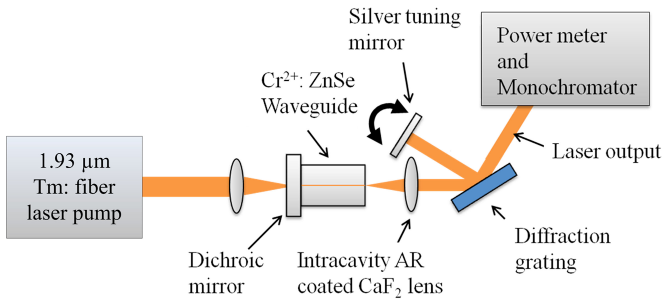

Fig. 1. Experimental arrangement of the Cr:ZnSe external-cavity waveguide laser in the Littman–Metcalf configuration.

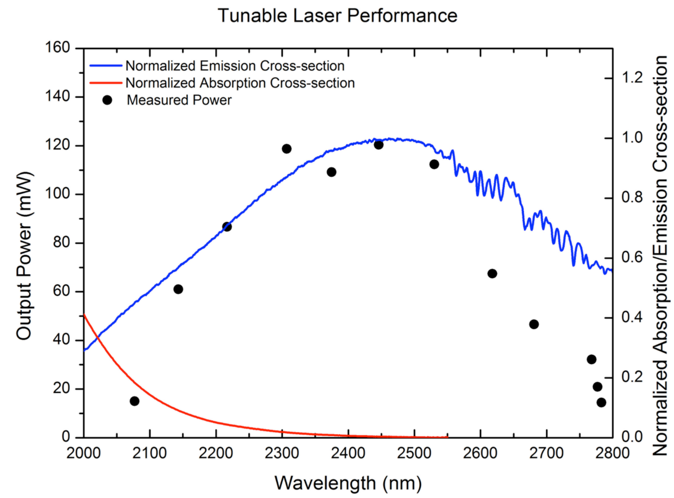

Fig. 2. Tunable Cr:ZnSe laser performance. Black dots represent measured output power at specific wavelengths. The blue and red line represent normalized emission and absorption cross-sections respectively for Cr:ZnSe.

laser at a range of speeds from 0.5–27 mm·s^{-1}. Structure diameters of 40, 60, 80, 120, 160 and 200 μm were fabricated with the number individual elements varied between 40 and 120. Each individual modification element was subject to multiple translations resulting in an "overscan" parameter with 1–51 overscans per element investigated. A more complete characterization of these structures is offered in [14], measuring propagation losses of 0.7 dB·cm^{-1}. Following waveguide fabrication the sample end facets were polished and AR coated for 1900–3000 nm.

III. Tunable Laser Characterization

The waveguides were built into an external-cavity in the Littman–Metcalf arrangement as displayed in Fig. 1. This configuration was chosen over the simpler Littrow configuration in order to avoid the variation in the laser output direction when tuning. The pump source was a CW Tm:fiber laser (AdValue Photonics) capable of producing 1.4 W of 1928 nm light after an optical isolator and power control. One of two separate dichroic mirrors was used at the pump input end of the cavity in order to achieve a high reflectivity across a wide wavelength range. The first dichroic mirror offered 99.9% reflectivity at 2050–2430 nm and the second 99.6% reflectivity at 2430–3000 nm, both were AR coated for the pump wavelength. The dichroic input mirrors were butt-coupled to the end facet of the waveguide and an AR coated 50 mm focal length CaF_2 plano-convex lens was used to couple the pump light into the waveguide. The emergent signal was collimated onto a 600 lines·mm^{-1}, 1600 nm blazed grating (Thorlabs GR13-0616) using an AR coated 20 mm focal length CaF_2 lens. The 2-in diameter silver tuning mirror was then rotated to tune the wavelength of the laser output. The tuning mirror was placed a distance of 40 mm from the grating so that light within the Cr:ZnSe emission band dispersed by the grating did not clip on the mirror edge.

The best performance was achieved with an 80 μm diameter waveguide which consisted of 80 individual modification elements fabricated with nine overscans. Laser output of over 15 mW was recorded across a range of 2077–2777 nm by rotating the tuning mirror. The laser output power was recorded at intervals across the wavelength range and is shown in Fig. 2. The maximum output power of 120 mW for 1150 mW pump was achieved at 2446 nm, in good agreement with the peak of the material emission cross section, see Fig. 2.

For wavelengths shorter than 2400 nm a mid-infrared optical spectrum analyzer (Yokogawa AQ6375) was used to measure the laser spectrum. Fig. 3 shows various laser spectra within the measureable range of the optical spectrum analyzer. The narrowest linewidth of 0.053 nm FWHM was obtained for the 2307 nm data point. It is important to note that the resolution of the optical spectrum analyzer was 0.05 nm and therefore the linewidth measurement may be instrument limited. A 300 mm monochromator (Gilden Photonics) was then used to measure the linewidth of the laser output at each recorded interval. An instrument limited FWHM spectral linewidth of 0.4 nm was recorded for each wavelength providing an upper bound across the full tuning range.

To investigate limitations in the tuning performance of the laser the system was numerically modelled using a plane wave approximation. Initially the pump and a guess value for the small signal power were converted to an irradiance based on the measured mode-field diameter. These irradiances are then co-propagated through the gain medium, which is split into 10^4 steps to allow for numerical modeling using steady state optical amplification equations adapted from Berry *et al.* [10], to include signal absorption and propagation losses for both the pump and signal. The signal emerging from the end of the gain medium is then multiplied by the manufacturers quoted transmittance for the intracavity optical elements at the given wavelength, i.e., the intracavity lens, the silver tuning mirror and the grating efficiency (Thorlabs GR13-0616). This signal irradiance is then propagated back through the gain element in the counter propagating direction and the sum of the two counter propagating signal irradiances at each spatial coordinate contribute to gain saturation. When the signal reaches the beginning of the waveguide it is multiplied by the reflectivity of the dichroic mirror and co-propagated with the pump

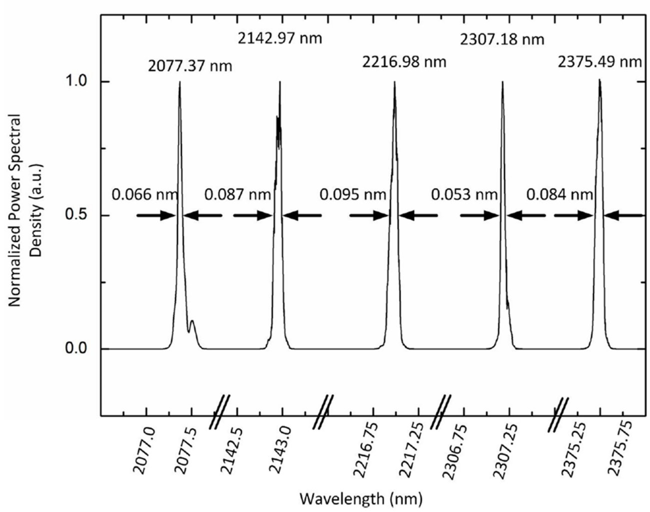

Fig. 3. Narrow linewidth spectra of the tunable Cr:ZnSe waveguide laser measured with a mid-infrared spectrum analyzer. A minimum linewidth of 0.053 nm is recorded at 2307 nm with all measured spectra demonstrating linewidths under 100 pm FWHM.

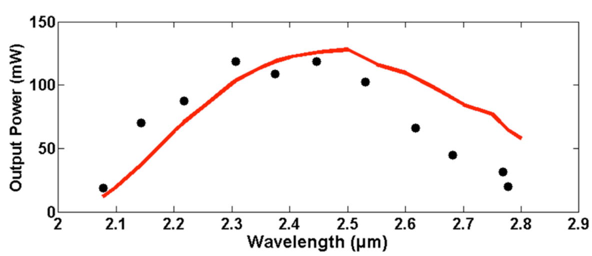

Fig. 4. Numerical model of tunable laser output and experimentally obtained data. Red line represents the theoretical model and black dots represent measured data points. No free fitting parameters have been used in the theoretical model.

again through the system. This process is repeated until the output power reaches a steady value. The propagation loss of the waveguide was assumed to be constant across the wavelength range of interest for the model at a value of 0.7 dB·cm^{-1}, as previously reported [14]. The measured values for Cr:ZnSe absorption and emission cross sections were used for each specific wavelength, see Appendix, and values for the grating and mirror reflectivities were taken from the manufacturers data (Thorlabs GR13–0616 and PF20-03-P01 respectively). For wavelengths above 2600 nm, the absorption cross-section of the material was taken to be zero. No arbitrary fitting factors were used for this model. The experimental results and the results of this model are shown in Fig. 4. Table I details the additional data used for the theoretical model.

Good agreement is observed over the entire tuning range but some deviation between modeled and experimental data can be seen, predominantly at the edges of the tuning range. This discrepancy is likely due to spectral dependence in the guiding characteristics of the waveguide. For short lasing wavelengths mode overlap between the pump and signal modes is better

TABLE I
CR:ZNSE WAVEGUIDE PROPERTIES USED FOR NUMERICAL MODEL OF THE LASER SYSTEM

Parameter	Fitted data
Waveguide propagation losses	0.7 dB·cm^{-1} [14]
Cr:ZnSe upper-state lifetime	4 μs [23]
Cr^{2+} ion concentration	8.5×10^{18} cm^{-3}(manufacturer data)
Waveguide length	6.0 mm
Mode field diameter (signal and pump)	40 μm [14]

due to the smaller separation of pump and signal wavelengths. At longer wavelengths the propagation losses due to radiation losses from the leaky mode are likely to increase [22]. The model also assumes a plane-wave, i.e., top hat pump and signal distribution, as well as a fixed signal irradiance across the entire tuning range. Characterization of the mode field and the associated propagation losses at each measured wavelength would serve to improve the accuracy of the model. Further to this, intra-cavity signal loss due to water absorption increases beyond approximately 2.6 μm causing a decrease in the efficiency of the laser system at longer wavelengths [18]. These factors account for the model over predicting the output powers for long wavelengths. Improved modeling could therefore be achieved by accurate measurement of the spectral dependence of the waveguide's propagation loss and incorporation of this data into the model. This model can be used to simply and quickly investigate the potential capabilities of similar systems built from different components, or different experimental configurations e.g., the model predicts a Littrow configuration built from the same components would be capable of 900 nm tunability, however the laser output changing direction with wavelength tuning significantly complicates integration of the Littrow configuration into compact sensing systems.

IV. CONCLUSION

An external-cavity waveguide laser was constructed based on a channel waveguide fabricated in Cr:ZnSe using ULI. The laser demonstrated 700 nm, 36.4 THz, of tunability in the 2077–2777 nm region with a maximum output power of 120 mW at 2446 nm corresponding to the peak of the Cr^{2+} emission cross-section. 36.4 THz is the widest tuning range demonstrated by any waveguide laser to the best of the authors' knowledge. The tunability is expected to be limited at either end by the waveguide propagation losses and the efficiency of the grating at the long wavelength limit. Narrow linewidth output as low as 53 pm (3 GHz) was measured at 2307.18 nm offering a mid-infrared widely tunable source suitable for applications in real world environments outside of the laboratory. Future work will concentrate on the integration of compact diode pump sources and investigation of integrated tuning elements allowing the production of environmentally stable, broadly tunable and compact mid infrared sources.

APPENDIX
Cr:ZnSe SAMPLE ABSORPTION AND EMISSION CROSS-SECTION DATA

Wavelength (nm)	Absorption Cross-section (cm^2)	Emission Cross-section (cm^2)
2077	2.31×10^{-19}	5.64×10^{-19}
2100	1.80×10^{-19}	6.13×10^{-19}
2143	1.14×10^{-19}	7.12×10^{-19}
2150	1.06×10^{-19}	7.27×10^{-19}
2200	6.39×10^{-20}	8.43×10^{-19}
2217	5.46×10^{-20}	8.91×10^{-19}
2250	4.10×10^{-20}	9.70×10^{-19}
2300	2.41×10^{-20}	1.08×10^{-18}
2307	2.24×10^{-20}	1.09×10^{-18}
2350	1.43×10^{-20}	1.17×10^{-18}
2375	1.10×10^{-20}	1.20×10^{-18}
2400	8.36×10^{-21}	1.22×10^{-18}
2450	4.98×10^{-21}	1.25×10^{-18}
2500	2.51×10^{-21}	1.24×10^{-18}
2550	2.61×10^{-21}	1.17×10^{-18}
2600	–	1.12×10^{-18}
2650	–	1.07×10^{-18}
2700	–	9.15×10^{-19}
2750	–	8.09×10^{-19}
2777	–	7.27×10^{-19}
2800	–	6.91×10^{-19}

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