Continuous-wave tunable 8.7-μm spectroscopic source pumped by fiber-coupled communications lasers

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Tunable narrow-band cw difference-frequency generation at 8.7 μm was demonstrated in silver gallium selenide ($AgGaSe_2$) at room temperature. The crystal was pumped by an injection-seeded Er/Yb-codoped fiber amplifier at 1.554 μm and a fiber-coupled diode-pumped monolithic ring Nd:YAG laser at 1.319 μm. The difference-frequency output was used for high-resolution spectroscopy of sulfur dioxide (SO_2). © 1996 Optical Society of America

The 8–12-μm wavelength region has been a target of high-resolution molecular spectroscopy and trace gas detection for many years, but the choice of a tunable cw narrow-band source operating in this region has been limited to lead-salt diode lasers and carbon dioxide lasers. These sources, although they are suitable for high-resolution molecular spectroscopy, suffer practical drawbacks such as large size, high power consumption and lack of wavelength tunability, and the need for cryogenic cooling. The use of diode lasers operating at the wavelengths of 1.3 and 1.5 μm as pump sources for difference-frequency generation (DFG) in $AgGaSe_2$ was proposed by Simon *et al.* in 1993.[1] The advantage of this scheme is the possibility of convenient generation of cw tunable narrow-band light in the spectroscopic fingerprint region 8–12 μm by readily available communications diode lasers. In addition, the use of fiber coupling for these sources can be expected to improve stability, eliminate the need for optical alignment, reduce the size, and lower the cost of the DFG source.

The recent development of Er/Yb-codoped fiber amplifiers[2] near 1.5 μm and of Pr^{3+}-doped fluoride fiber amplifiers[3] near 1.3 μm has made optical single-frequency output power in excess of 100 mW available. Such sources can be used for tunable low-noise cw DFG at the microwatt level between 8 and 12 μm. This radiation can be used for high-resolution mid-infrared molecular spectroscopy and, potentially, for spectroscopic detection and measurement of trace air contaminants such as ammonia, ethylene, sulfur dioxide, methane, nitrous oxide, and phosphine.

Here we report the implementation and successful operation of a compact all-solid-state room-temperature DFG source (see Fig. 1) that employed a high-power Er/Yb-codoped fiber amplifier pumped at 1.064 μm. The amplifier was injection seeded by an optically isolated 2-mW pigtailed distributed-feedback (DFB) diode laser at 1.554 μm and operated near saturation, producing as much as 0.5 W of single-frequency power. Figure 2 shows the amplifier output power with injection seeding versus launched pump power at 1.064 μm. The pump threshold of 87 mW and a slope efficiency of 12% were determined from these data. The relatively low[2] slope efficiency is attributed to incomplete saturation, a nonoptimal copropagating pump arrangement, and operation at a wavelength that is ~20 nm away from the gain peak. After optical isolation, which was accompanied by a 20% loss in power, the amplifier output was combined with the output of a 35-mW diode-pumped monolithic ring Nd:YAG laser (Lightwave Electronics Model 122) at 1.319 μm in a polarizing cube beam splitter.

Later in the experiment an alternative optical setup was implemented in which the pump (1.319 μm) and the signal (1.554 μm) beams were combined in a single-mode fiber by a fiber-optic wavelength-division multiplexer. This arrangement provided the stable, alignment-free spatial and angular beam overlap required for optimal DFG conversion efficiency. In both cases the polarization controllers were adjusted to produce linear orthogonal polarizations of the pump and the signal beams at the crystal input.

The difference-frequency mixing was performed in a 4 mm × 4 mm × 10 mm $AgGaSe_2$ crystal (Cleveland

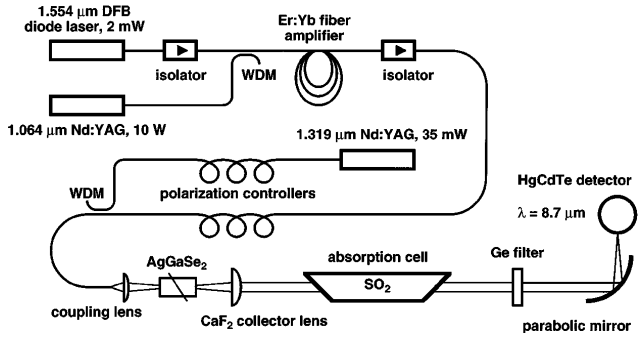

Fig. 1. Schematic of an 8.7-μm tunable single-frequency cw DFG source pumped by fiber-coupled diode and solid-state lasers operating at 1.319 and 1.554 μm. A wavelength-division multiplexer (WDM) was used to combine the two beams in a single fiber before mixing so that no adjustment of the beam overlap was necessary. The source was used for high-resolution spectroscopy of SO_2.

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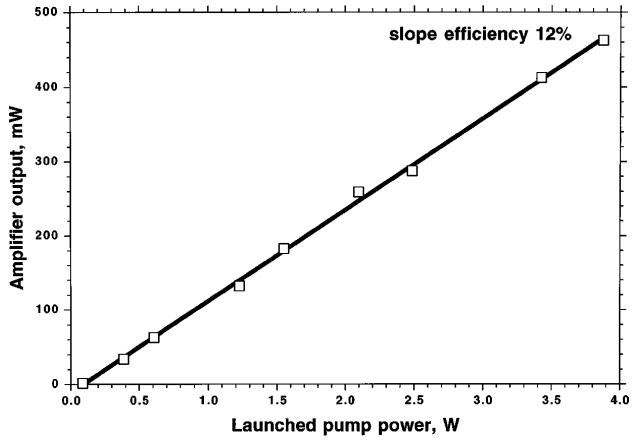

Fig. 2. Output power from an Er/Yb-codoped fiber amplifier before a Faraday isolator versus launched pump power at 1.064 μm. The amplifier is injection seeded by a 2-mW DFB diode laser at 1.554 μm.

Crystals, Inc.) cut for type 1 phase matching at an internal angle of 65°. The actual phase-matching angle θ used in the experiment was 68.4°, which was readily accessible with a given crystal aperture and required an external incidence angle of 9°. In the arrangement using the polarizing cube beam splitter the pump and the signal beams were focused into the mixing crystal by an $f = 5$ cm lens. The beam waists inside the crystal were 15.5 and 18.8 μm, respectively, calculated from the measured waists of collimated beams. No attempt was made to achieve optimal focusing.[4] The effective crystal length was limited by the birefringent beam walk-off:

$$\tan \rho = 1/2 \sin 2\theta n(\lambda, \theta)^2 |n_e(\lambda)^{-2} - n_0(\lambda)^{-2}| .$$

Here $n_0(\lambda)$, $n_e(\lambda)$, and $n(\lambda, \theta)$ are the ordinary, the extraordinary, and the angle-dependent indices of refraction respectively, of $AgGaSe_2$.[5] The walk-off angle calculated for the pump wavelength of 1.319 μm is 0.39°, which corresponds to an effective crystal length of 2.5 mm.

The difference-frequency output at 8.7 μm (idler) was collected by an $f = 5$ cm CaF_2 lens, transmitted through a 4-mm-thick uncoated Ge filter, and focused onto a liquid-N_2-cooled HgCdTe detector by an $f = 5$ cm off-axis parabolic mirror. With 29-mW pump power and 370-mW signal power incident upon the crystal, an idler power of 0.1 μW was measured. After correction for reflection losses from the uncoated Ge filter and facets of the $AgGaSe_2$ crystal, this corresponds to 0.4 μW of power generated inside the crystal. This power level is 35% less than expected from a 2.5-mm-long crystal under the conditions of optimal focusing.[4] This discrepancy may be attributed in part to improper mode matching of the pump and the signal beams. However, it was also established in the course of the experiment that the detector active area of 0.25 mm^2 was not sufficient to collect all the idler output because of the larger spot size at the focus of the parabolic mirror. The spot size was increased primarily by improper alignment of the mirror and by spherical aberrations in the collector lens that was used to collimate a rapidly diverging idler beam 8.7 μm.

The typical detected idler power 0.1 μW was sufficient for high-resolution spectroscopy considering that the noise equivalent power the HgCdTe detector was 3×10^{-12} W/$\sqrt{\text{Hz}}$, which corresponds to an equivalent absorption of $3 \times 10^{-5}/\sqrt{\text{Hz}}$. A 10-cm-long absorption cell with CaF_2 Brewster windows filled to 5 Torr with sulfur dioxide was introduced into the idler beam for spectroscopic measurements. Initially, we performed the frequency tuning by sweeping the drive current of the DFB seed laser at 1.554 μm. However, the current tuning response of the laser was not sufficient to permit frequency scans longer than 5 GHz, thereby making it difficult to identify the observed absorption lines. We therefore used instead temperature tuning of the Nd:YAG pump laser at 1.319 μm. A tuning rate of 0.02 Hz was selected to permit faster data acquisition without distortion of linearity of the frequency sweep. The pump beam was chopped at a rate of 2 kHz. The idler power was lock-in detected without regard to phase and recorded with an 8-bit digital oscilloscope. The observed infrared transitions of sulfur dioxide were assigned by a HITRAN database.[6] Figure 3 shows the direct absorption spectrum of the ν_1 symmetric stretch band of sulfur dioxide near 1144 cm^{-1}. The frequency sweep was reproducible and linear over at least half of a wave number, which is the maximum continuous sweep range available with the pump laser used in this experiment.

In summary, we have demonstrated an all-solid-state room-temperature cw narrow-band source tunable near 8.7 μm. The source is based on difference-frequency mixing of a fiber-coupled diode-pumped monolithic ring Nd:YAG laser 1.319 μm and an Er/Yb-copdoped fiber amplifier in type 1 critically phase-matched $AgGaSe_2$. The fiber amplifier was pumped at 1.064 μm and injection seeded by a pigtailed DFB laser diode at 1.554 μm. Alternatively, a 1.3-μm extended-cavity diode laser in conjunction with a Pr^{3+}-doped fluoride fiber amplifier can replace the Nd:YAG laser at 1.319 μm, thereby providing higher

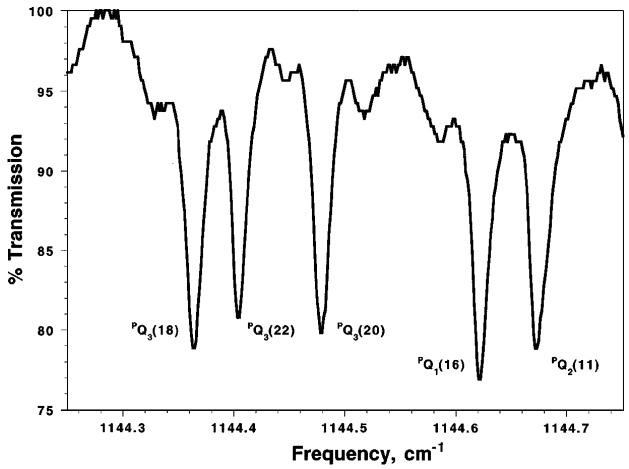

Fig. 3. Optical transmission of 10-cm-long Brewster window absorption cell filled with SO_2 at a pressure of 5 Torr. The sweep time was 50 s, the lock-in amplifier time constant was 0.1 s (12 dB/octave roll-off), and the choppler frequency was 2 kHz. The signal was detected without regard to phase (R component).

pump power and permitting fast continuous frequency scans of 10 cm^{-1} or more. With 29 mW of pump power and 370 mW of signal power incident upon the mixing crystal, 0.1-μW idler power was detected. The DFG source was applied to high-resolution spectroscopy of the ν_1 symmetric stretch band of SO_2. This, to our knowledge, is the first reported cw all-diode-pumped spectroscopic DFG source operating at a wavelength above 8 μm at room temperature. Furthermore, the source uses commercial single-frequency pigtailed diode and diode-pumped solid-state lasers operating near the fiber communications wavelengths of 1.3 and 1.5 μm. Although limited infrared tuning range and output power have been demonstrated in the experiment, both can be improved by replacement of the pump sources. With the use of two 300-mW fiber amplifiers injection seeded by tunable extended-cavity diode lasers near 1.3 and 1.5 μm, for example, the DFG output power can be increased to 5 μW, whereas the tuning range can be extended from 900 to 1400 cm^{-1}. These projected performance characteristics will benefit applications such as high-resolution molecular spectroscopy and trace-gas detection.

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