Difference-frequency mixing in $AgGaS_2$ by use of a high-power GaAlAs tapered semiconductor amplifier at 860 nm

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As much as 47 μW of cw infrared radiation and 89 μW of pulsed infrared radiation, tunable near 4.3 μm, have been generated by mixing the outputs of a high-power tapered semiconductor amplifier at 858 nm (signal wave) and a $Ti{:}Al_2O_3$ laser at 715 nm (pump wave) in $AgGaS_2$. The GaAlAs tapered traveling-wave amplifier delivered as much as 1.5 W of diffraction-limited cw power into the nonlinear crystal. Output powers, conversion efficiencies, and spectral characteristics of this novel midinfrared source are discussed.

Recent advances in the development of new and improved nonlinear optical materials, such as $AgGaS_2$ and $AgGaSe_2$, now offer a convenient technique of generating cw tunable infrared narrow-band coherent radiation over a wide wavelength range (3 to 18 μm) by means of difference-frequency generation[1,2] (DFG). Therefore, unlike conventional infrared lasers, a single DFG setup based on these materials can cover the entire spectroscopically rich portion of the infrared region. The use of semiconductor diode lasers as pump sources in the nonlinear DFG process is particularly promising, as their compact size and ease of operation permit the construction of a portable and robust infrared laser source for sensitive and selective environmental monitoring of trace species However, the nonlinear frequency conversion efficiency of all-diode-laser DFG sources has been limited in the past by the relatively low-power output of commercially available single-mode III–V diode lasers. Recently we reported several nanowatts of cw infrared radiation[3] obtained by difference-frequency mixing of two visible low-power laser diodes (2 and 10 mW) in $AgGaS_2$. The DFG conversion efficiency can be increased, however, either by using optical semiconductor amplifiers to boost the power output of the single-frequency diode lasers or by putting the nonlinear crystal in an external enhancement cavity or in the laser cavity[4] of one of the pump lasers.

Significant progress has been made in obtaining diffraction-limited coherent radiation from high-power laser-diode arrays and broad-area laser diodes[5,6] and, more recently, traveling-wave amplifiers.[7] When seeded by a single-stripe low-power master diode laser,[7] the semiconductor amplifier has been demonstrated to generate near-diffraction-limited, single-longitudinal-mode emission required for applications such as nonlinear frequency conversion through second-harmonic generation[8] and sum-frequency mixing.[9] Under pulsed operation, 11.6 W of peak power was generated by a broad-area amplifier seeded by a laser diode.[7] High-power cw amplifier operation, required for many applications, has been considerably more difficult to achieve. Recently, however, 5.25 W of cw emission[10] was obtained from a tapered-stripe[7,11] GaAlAs amplifier seeded with a $Ti{:}Al_2O_3$ laser.

In this Letter we describe difference-frequency mixing of a high-power GaAlAs tapered traveling-wave semiconductor amplifier with a cw $Ti{:}Al_2O_3$ laser in a 45-mm-long $AgGaS_2$ crystal cut for type I noncritical phase matching at room temperature. The amplifier was injection seeded by a single-mode index-guided master diode laser. The amplifier was operated in a cw and pulsed mode to permit an investigation of the DFG conversion efficiency in $AgGaS_2$ at high pump power levels.

The experimental setup used in this research is shown in Fig. 1. The master laser was an index-guided diode laser (Spectra Diode Laboratories Model SDL5410C) emitting as much as 130 mW of power in a single longitudinal mode around 860 nm with a less-than-20-MHz linewidth. By changing the temperature, we can tune the laser wavelength over ~1–2 nm. The amplifier chip was bonded active side down on a heat sink, which in turn was attached to a water-cooled fixture and permitted unobstructed

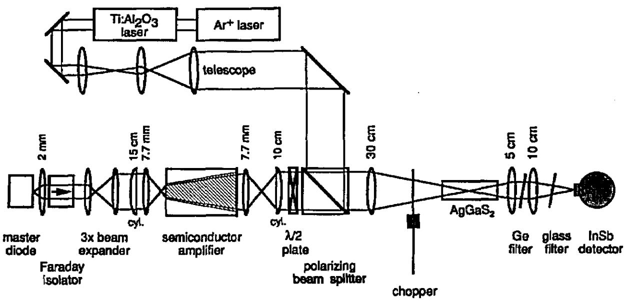

Fig. 1. Experimental setup used to mix the outputs of a GaAlAs tapered amplifier and a $Ti{:}Al_2O_3$ laser in $AgGaS_2$ cut for 90° type I phase matching. The amplifier was seeded by a cw single-mode master laser diode.

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optical access to both facets. After collimation by an $f = 2.0$ mm lens (Corning Model 350150, 0.5 N.A.), the master laser beam passed through a Faraday isolator and a 3× beam expander composed of an $f = 8.6$ mm lens (NRC Model FL-20) and an $f = 25.6$ mm lens (Melles-Griot Model 06 GLC 004). Final coupling of the injected signal into the amplifier was accomplished by a combination of a closely (3 cm) spaced $f = 15$ cm cylindrical lens and a high-N.A. $f = 7.7$ mm lens (Fujinon Model LSR-F35B, 0.5 N.A.). The cylindrical lens served to move the focus point to several hundred micrometers in front of the facet in the junction plane.[7] This highly astigmatic input resulted in Gaussian input beam widths of approximately 150 μm in the junction plane and 1 μm in the perpendicular plane. With 100 mW of master laser power incident upon the amplifier, 38 mW of power was coupled into the amplifier. The coupling efficiency was low compared with the 60–70% typically measured with a Ti:sapphire laser, a fact attributed to underfilling of the 7.7-mm focusing lens *in the plane perpendicular to the junction* by the noncircular laser diode beam. The GaAlAs tapered amplifier used in this research is characterized by a 250-μm input width, a 500-μm output width, a 1.5-mm length, and a single-quantum-well separate confinement heterostructure active region. At high currents the amplifier had a peak gain near 860 nm. The facets of the amplifier were antireflection coated ($R \approx 10^{-3}$) at 860 nm for single-pass traveling-wave operation. A second $f = 7.7$ mm lens, positioned one focal length away from the facet, was used to collimate the amplifier emission perpendicular to the junction. In the junction plane, a focused spot approximately 8 cm to the right of the lens was formed, corresponding to a magnified image of the virtual input point source in front of the amplifier. Finally, the output beam was collimated by an $f = 10$ cm cylindrical lens positioned one focal length from the focused spot. This optical arrangement resulted in a collimated output beam with a nearly square crosssection.

The pump wave was provided by a $Ti:Al_2O_3$ ring laser (Coherent Model 899) operated at 715 nm, close to its short-wavelength operation limit. In order to maximize the power output, we operated the laser multilongitudinal mode without intracavity étalons, resulting in a linewidth of ~1 GHz. Pump and signal wave polarizations were chosen perpendicular to each other for 90° type I phase matching in $AgGaS_2$. Both beams were overlapped by a polarizing beam splitter and focused into the 45-mm-long $AgGaS_2$ crystal with a 30-cm focal-length lens. A scanning slit beam profiler (Beamscope, Merchantek Inc.) was used to measure and optimize the beam-waist widths as well as the lateral and longitudinal beam overlap. A three-lens telescope design in the pump laser beam path permitted matching of beam-waist widths and focal points for the two beams at the location corresponding to the center of the crystal. The beam waists (half-width at $1/e^2$ maximum) were set to ~33 μm in both vertical and horizontal planes, close to optimum focusing.[1] As measured with the beam profiler, the spatial distribution of pump and signal beams was near Gaussian, whereas in the case of the signal wave (amplifier) approximately 20% of the focused light was in sidelobes outside the main Gaussian envelope.

The amplifier output power incident upon the nonlinear crystal was measured with an integrating sphere detector as a function of the amplifier current and is shown in Fig. 2. We obtained a maximum signal wave power of 1.5 W under cw operation and 3.2 W under pulsed operation with 50-μs-long pulses and a 0.1% duty cycle. After correcting for the 75% capture efficiency of the $f = 7.7$ mm lens and transmission losses of the beam splitter and other optical components, we measured the actual amplifier output at the maximum cw current of 6 A to be 2.5 W. The maximum operating currents for the amplifier were arbitrarily chosen and do not represent a fundamental operating limit of the amplifier.

The difference-frequency long-wavelength radiation generated in the $AgGaS_2$crystal was collimated with a 5-cm focal-length CaF_2 lens and focused onto a liquid-N_2-cooled photovoltaic InSb detector with a sensitive area element of 4-mm diameter (Graseby Infrared IS-4). An antireflection-coated germanium filter was used to block the pump and signal waves and pass the difference-frequency radiation. To avoid saturation of the detector–preamplifier combination at the highest powers obtained under pulsed amplifier operation, we placed a glass filter ($T = 2.8\%$ at 4.3 μm) in front of the detector to attenuate the detector signal. Phase matching was found to occur at wavelengths of 714.60 and 858.60 nm for the pump and the signal wave, respectively, corresponding to a generated difference-frequency wavelength of ~4.26 μm (2350 cm^{-1}). The laser wavelengths were determined with a spectral resolution of ~0.1 nm and an absolute spectral accuracy of ~0.1 nm with a multimode probe fiber connected to an optical spectrum analyzer (HP 70951 A optical spectrum analyzer). The phase-matching bandwidth was observed to be of the order of the spectral resolution of the optical spectrum analyzer. Tuning of the infrared wavelength was

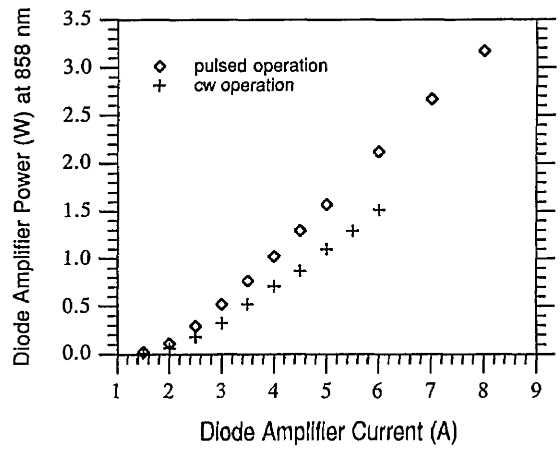

Fig. 2. Amplifier output power in cw and pulsed operation as measured with an integrating sphere detector. Approximately 38 mW of the incident master laser cw power was coupled into the amplifier.

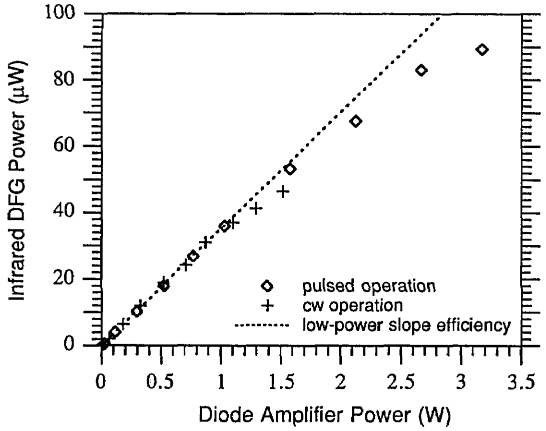

Fig. 3. Generated infrared DFG $\lambda \approx 4.3$ μm power as a function of the amplifier power incident upon the crystal for cw and pulsed modes of operation. The $Ti{:}Al_2O_3$ laser cw power was fixed at 330 mW.

limited to ~25 cm^{-1} by the limited temperature tuning range of the master diode laser.

Figure 3 shows the generated infrared DFG power as a function of the diode amplifier output power for cw and pulsed amplifier operation. Values shown are corrected for the 4.3-μm transmission loss of the optical components between the crystal and the detector but not for the 17% Fresnel reflection at the crystal output facet. For all measurements the $Ti{:}Al_2O_3$ laser output was fixed at a cw power of ~330 mW and we changed the diode amplifier output power by varying the pump current. The dotted line indicates the low-power external slope efficiency of ~35 μW/W for the DFG process. Maximum difference-frequency powers of 47 and 89 μW were obtained for cw and pulsed operation, respectively. The drop in experimental slope efficiency at high amplifier power levels is attributed to the degradation in the diode laser beam quality occurring at the highest amplifier currents. To evaluate the contribution of thermal effects in the mixing crystal to the drop in slope efficiency at high amplifier power levels, we determined the absorption loss in the $AgGaS_2$ crystal at the signal wavelength. From the ratio of transmitted to reflected signal power we found the absorption in $AgGaS_2$ at 858 nm to be as low as ~1 to 1.5% cm^{-1}. At high signal power levels, no decay of the infrared pulse amplitude during the 50-μs pulse was observed, indicating that thermal lensing did not contribute to the drop in experimental slope efficiency occurring at the highest pulsed powers. Correction for the Fresnel reflection losses for pump, signal, and idler waves at the surfaces of the uncoated $AgGaS_2$ crystal, the germanium filter, and the CaF_2 lenses results in an internal slope efficiency of ~65 μW/W at 330 mW of cw $Ti{:}Al_2O_3$ pump power. No significant improvement in the slope efficiency was observed when we changed the $Ti{:}Al_2O_3$ laser from multimode to single-mode operation by inserting the intracavity étalons into the ring laser cavity.

In conclusion, as much as 47 μW of cw and 89 μW of pulsed infrared radiation around 4.3 μm have been generated by difference-frequency mixing the outputs of an injection-seeded GaAlAs tapered semiconductor amplifier (the signal source) and a $Ti{:}Al_2O_3$ ring laser (the pump source) in $AgGaS_2$ by using type I noncritical phase matching. An internal slope efficiency of 65 μW/W has been achieved at 330 mW of cw $Ti{:}Al_2O_3$ pump power. Further improvements in system efficiency and compactness should be possible through the use of an all-diode system, for which combinations of GaAlAs amplifiers in the range of 750–860 nm and InGaAsP amplifier below 700 nm could be used to achieve the specific midinfrared wavelengths. The midinfrared source presented is promising for wide range of applications, including chemical analysis, remote sensing, pollution detection, and medical research.

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