50-W CW Single Frequency 589-nm FASOR

Craig A. Denman, Paul D. Hillman, Gerald T. Moore, John M. Telle, Joseph E. Preston, Jack D. Drummond, and Robert Q. Fugate
Air Force Research Laboratory, Directed Energy Directorate, Starfire Optical Range
3550 Aberdeen Avenue SE, Kirtland AFB, NM 87117

Abstract: Doubly resonant sum-frequency generation in LBO has produced a CW, 50-W, single-frequency, diffraction-limited, linearly-polarized, 589-nm beam from injection-locked Nd:YAG lasers operating at up to 100 watts at 1064 nm and 60 watts at 1319 nm.

OCIS codes: (140.3520) Lasers, injection-locked; (190.2620) Frequency conversion; sum-frequency generation; sodium guidestar; single-frequency lasers.

Introduction

Two years ago at this meeting [1] we reported the operation of a 20-W CW solid-state Na guidestar excitation source based on doubly resonant sum-frequency generation (SFG) of light from two Nd:YAG ring lasers operating at 1064 nm and 1319 nm. It has been tempting over this period of time to refer to this device producing 589 nm coherent light as a LASER (Light Amplification by Stimulated Emission Radiation); however, we know that this is not the correct use of the acronym. To circumvent this quandary, we have referred to this device as a sodium guidestar SFG system, or a sodium guidestar excitation pump source. We would like to introduce a new acronym, FASOR (Frequency-Addition Source of Optical Radiation), to simplify future references to such an SFG-based coherent source – a FASOR refers to more than just an SFG cavity but rather the entire system. Figure 1 is a block diagram showing the four main subsystems of the sodium guidestar FASOR.

Further work with the original 20 W 589-nm FASOR demonstrated that an 8.5 W beam (limited due to projection optics losses), converted to circular polarization, generated a guidestar producing a photon return of 840 photons/cm^2/sec (Summer-time column density) from the mesospheric sodium layer at about 90-km altitude. [2,3] This is ample for most astronomical adaptive optical telescopes. Circular polarization enhances the photon return because of optical pumping of the magnetic sub-levels of sodium [4]. However, a higher power FASOR, more than 20 watts, is desirable for imaging moving targets such as satellites [5]. Also, astronomical observatories can split the light from a more powerful FASOR to produce multiple guidestars for multi-conjugate adaptive optical telescope systems.

We report here on the operation of a 50 W 589-nm FASOR based on the same principle as our earlier device: However, a major difference, besides the increased power is that it is computer operated and monitored. The FASOR has been mounted on the azimuthal stage of the 3.5-m telescope at the Starfire Optical Range and its various operating modes automated. In addition, we report on the operation of the injection-locked Nd:YAG rod-based ring lasers that have produced 100 watts at 1064 nm and 60 watts at 1319 nm. The output powers for 589 nm and for 1319 nm are the highest reported to date for CW single frequency solid-state laser sources – over the past two

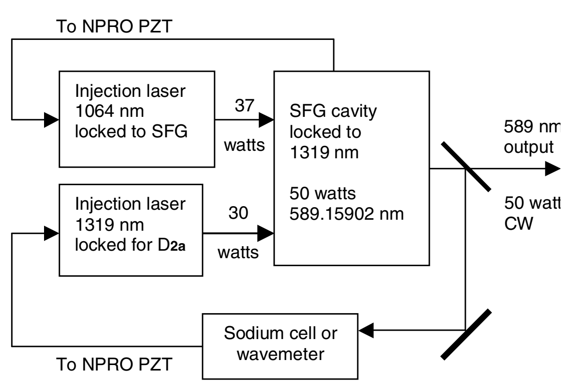

Fig. 1. Block diagram showing the four major functional components of an optimized 50 W, CW, single frequency, 589-nm FASOR.

years, we have increased the powers from 20 to 50 watts at 589 nm and from 24 to 60 watts at 1319 nm. Prior to this, single frequency, CW, solid-state sources at these wavelengths did not exist over 1 W power levels. The 589-nm FASOR at this new power level is an enabling technology for large ground-based adaptive optical telescopes worldwide.

The 50-W Sodium Guidestar FASOR System

Figure 2 is a schematic drawing illustrating the optics and locking electronics of the 50-W FASOR. The external SFG cavity is simultaneously resonant to two single frequency injection-locked lasers operating at the two strong lines of Nd:YAG: 1064 nm and 1319 nm. The SFG cavity length is first adjusted and locked to resonate at the wavelength of the 1319-nm NPRO and then the wavelength of the 1064-nm NPRO is adjusted to be resonant with the SFG cavity. Light at the sodium D_{2a} line is produced in the SFG cavity in a lithium triborate (LBO) crystal. The injection-locked lasers use multiple "engines" manufactured by Lightwave Electronics Corporation to power the ring slave oscillators. Each engine contains a diode laser side pumped Brewster-cut Nd:YAG rod. These engines are more powerful than the engines used in our 20-W FASOR: That FASOR used two engines for each ring oscillator. The present FASOR uses four engines for the 1064-nm ring oscillator and six engines for the 1319-nm ring oscillator. When injection locked, the 1064-nm laser produces 80 – 100 watts with $M^2 < 1.1$, and the

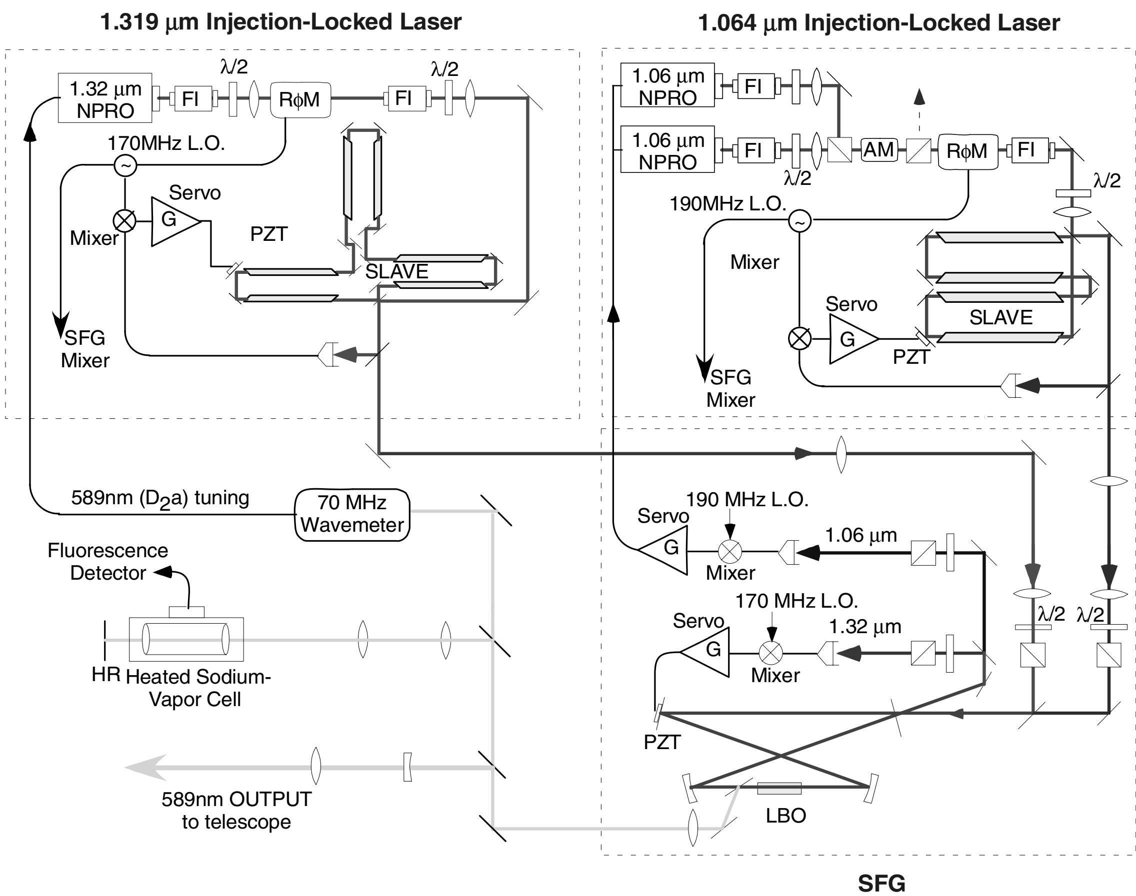

Fig. 2. Schematic drawing of the two injection-locked lasers, the SFG cavity, and the locking electronics for the 50-W FASOR. The phase sidebands generated by the resonant phase modulators are used by both injection locking and SFG electronics utilizing the same local oscillator.

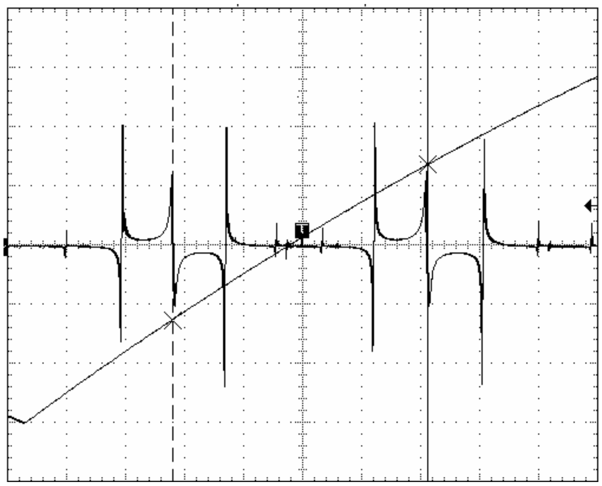

Fig. 3. PDH zero-crossing error signal used for providing feedback to the 1064-nm slave ring oscillator. Sideband frequency is 190 MHz and the slave ring FSR is 240 MHz; hence, the sidebands "overlap" the cavity FSR. Shown is a single scan spanning two FSR's, the piezo-mounted mirror ramp, and marking cursors.

Fig. 4. The 1319-nm slave ring oscillator PDH error signal. Sideband frequency is 170 MHz and the slave ring FSR is 219 MHz; hence, sidebands "overlap" cavity FSR. Shown is a scan that changes direction in the middle of the trace, and the piezo-mounted mirror ramp. The NPRO temperature is set to 45C to specifically show unexplained frequency-pulling behavior.

1319-nm laser produces 60 watts with the same beam quality. The ring oscillators are injection-locked to single frequency non-planar ring oscillators (NPRO), also manufactured by Lightwave Electronics Corporation, using the Pound-Drever-Hall (PDH) technique. The linewidth of the injection-locked lasers follow closely to that of their respective seed NPRO source. In order to produce a PDH error signal for locking the ring oscillators, as well as the SFG cavity, electro-optic modulators are used to impose phase sidebands on the outputs of the NPRO lasers. These sidebands are at 190 MHz for the 1064-nm laser and 170 MHz for the 1319-nm laser (see Figs. 3 and 4). These frequencies are much higher than we used in the 20-W FASOR, in order to lie outside the wider resonance bandwidth of the SFG cavity. The 50-W FASOR contains two 1064-nm NPRO lasers with the capability of rapid electro-optic switching from one NPRO to the other. By tuning these two NPRO's to slightly different frequencies, we expect that this switching can be used to blink the sodium guidestar on and off while leaving the intensity of the Rayleigh scattering from the lower atmosphere essentially unchanged. When locked, the ring lasers operate unidirectionally at the NPRO frequencies. The NPRO frequencies can be tuned to a limited extent, either slowly by changing the NPRO temperatures or rapidly by means of internal piezoelectric (PZT) actuators.

The 1064-nm and 1319-nm light is mode matched and combined by a dichroic element into the SFG cavity. The SFG cavity is a bowtie resonator similar to that used in the 20-W FASOR, except that the input coupler has a lower reflectivity (~90%), as appropriate for the higher nonlinear loss expected at higher power. One of the SFG cavity mirrors is mounted on a PZT for fine adjustment of the cavity length to resonate the 1319-nm light. The frequency of the 1064-nm NPRO, and consequently the 1064-nm ring oscillator, is tuned so that this wavelength also resonates in the SFG cavity. The SFG cavity contains an antireflection-coated 2-cm LBO crystal oriented for type-I noncritical phase matching at about 40º C. A coated Brewster-angle scraper mirror following the crystal reflects the s-polarized 589-nm light out of the cavity, while transmitting the p-polarized infrared light. The SFG is used as a Fabry-Perot spectrum analyzer during alignment and system characterization (see Figs. 5 and 6). Because of the doubly resonant nature of the FASOR design, the SFG cavity acts as a 'mode cleaner', and the 589-

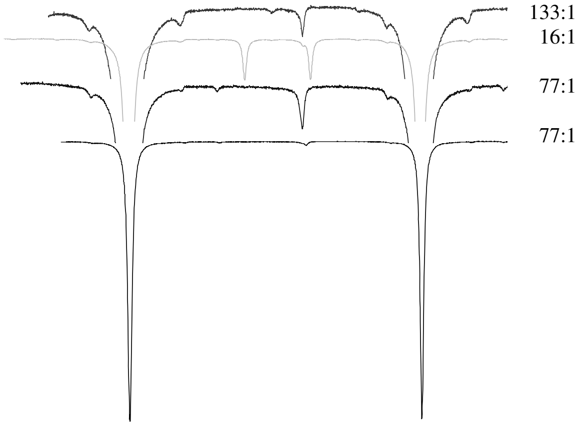

Fig. 5. The sum-frequency generator is used as a Fabry-Perot spectrum analyzer for both 1064nm and 1319nm, separately. Because the SFG-FP operates with the LBO installed and at temperature, some SHG nonlinear loss occurs when analyzing a high power input beam. Here, the 1064-nm NPRO and injection-locked lasers are analyzed (with arbitrary vertical scales): top trace is NPRO only without phase sidebands; second trace from top is NPRO only with phase sidebands; third trace is the injection laser with 80 watts incident onto SFG cavity with scale zoomed in to show detail; last trace is injection laser with 80 watts and at full scale. The ratio of fundamental mode to off-axis mode is as indicated.

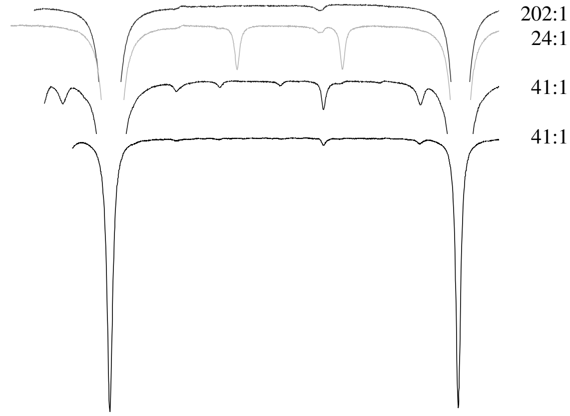

Fig. 6. The SFG-FP traces for 1319nm. Here, the 1319-nm NPRO and injection-locked lasers are analyzed (with arbitrary vertical scales): top trace is NPRO only without phase sidebands; second trace from top is NPRO only with phase sidebands; third trace is the injection laser with 60 watts incident onto SFG cavity with scale zoomed in to show detail; last trace is injection laser with 60 watts and at full scale. Ratio of fundamental mode to off-axis mode is as indicated. Note that this ratio is reduced, to some degree, due to the SHG nonlinear loss when the circulating power peaks. The ratios are obtained through routine alignment: indicating single-frequency operation and good mode matching.

nm beam quality is diffraction limited. A wavemeter with a 70-MHz accuracy or Doppler-free saturation spectroscopy in a Na vapor cell is be used to tune the yellow light exactly to the Na D_{2a} absorption line.

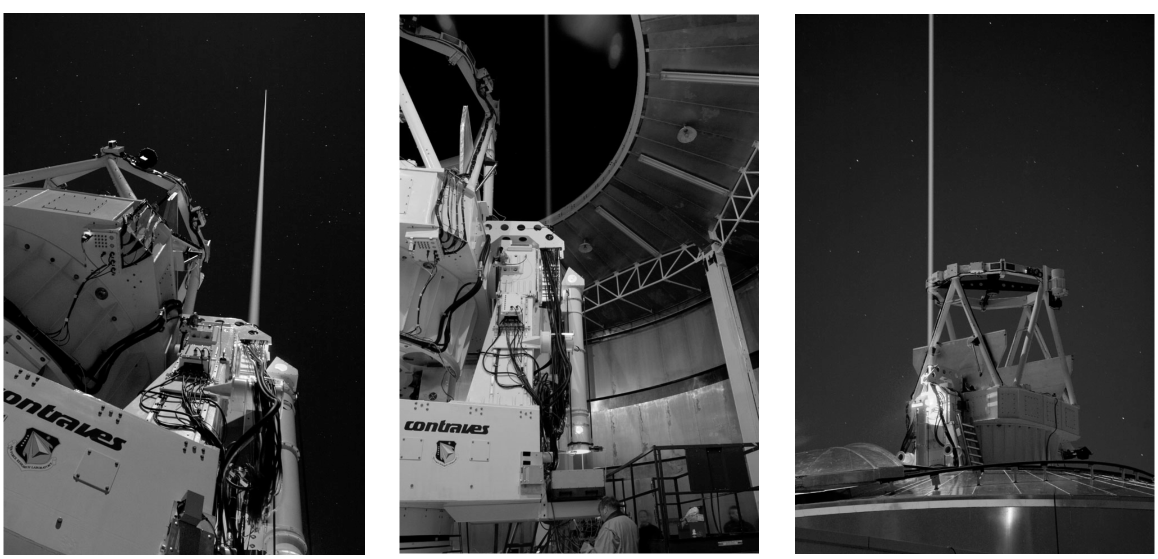

Fig. 7. Photographs of the 50-W FASOR operating on the 3.5-m telescope at the Starfire Optical Range.

Concluding Remarks

Single frequency, CW, linearly polarized, and diffraction-limited power levels of 100 watts at 1064 nm, 60 watts at 1319 nm, and 50 watts at 589 nm are reported. Those powers at 1319 nm and 589 nm represent significant new results for single frequency solid-state laser sources. Because of our user-driven schedule to mount onto a telescope [6], the operation of our 50-W FASOR has not been as well characterized as our 20-W FASOR. The efficiency is lower, and the power at 589 nm is considerably lower than expected from theory [7] while attempting to impedance match at the highest pump power levels. Further characterization and analysis may lead to better optimization and yield higher power. It is encouraging that, in spite of large circulating infrared powers (estimated up to several kW), there has been no damage to the LBO crystal or to the optical coatings. Photographs of the 50-W FASOR during initial operation tests on the 3.5-m telescope at the Starfire Optical Range are shown in Fig. 7. The injection-locked laser properties are summarized in Tables 1 and 2.

Table 1. 1064 nm Injection Laser Properties.

Attribute		Value or Range
80 W Injection to NPRO power		>178:1
100 W Injection to NPRO power		>222:1
NPRO power at input coupler		450 mW
Injection laser free spectral range		240 MHz
PDH sideband frequency		190 MHz
Lock range:	Measured at 80 W	3.0 MHz
	Calculated at 80 W	2.9 MHz
	Calculated at 100 W	2.6 MHz
Beam quality, M^2		<1.1

Table 2. 1319 nm Injection Laser Properties.

Attribute		Value or Range
60 W Injection to NPRO power		>315:1
NPRO power at input coupler		190 mW
Injection laser free spectral range		219 MHz
PDH sideband frequency		170 MHz
Lock range:	Measured at 60 W	540 kHz
	Calculated at 60 W	1.2 MHz
Beam quality, M^2		<1.1

References

1. J. C. Bienfang, C. A. Denman, B. W. Grime, P. D. Hillman, G. T. Moore, and J. M. Telle, “20 watt CW all-solid-state 589-nm sodium beacon excitation source based on doubly resonant sum-frequency generation in LBO,” OSA *Trends in Optics and Photonics Vol. 83, Advanced Solid-State Photonics, J. J. Zayhowski, ed.* (Optical Society of America, Washington, DC 2003), pp. 111 – 120.
2. J. C. Bienfang, C. A. Denman, B. W. Grime, P. D. Hillman, G. T. Moore, and J. M. Telle, “20 watt of continuous-wave sodium D_2 resonance radiation from sum-frequency generation with injection-locked lasers,” Opt. Lett. **28**, 2219 – 2221 (2003).
3. J. Drummond, J. Telle, C. Denman, P. Hillman, and A. Tuffli, “Photometry of a sodium laser guide star at the Starfire Optical Range. II. Compensating the pump beam,” Publications of the Astronomical Society of the Pacific, **116**, 952 – 964 (2004).
4. W. Happer et al, “Atmospheric-turbulence compensation by resonant optical backscattering from the sodium layer in the upper atmosphere,” JOSA A **11**, 263 – 275 (1994).
5. J. M. Telle, P. W. Milonni, and Paul D. Hillman, “Comparison of pump-laser characteristics for producing a mesospheric sodium guidestar for adaptive optical systems on large aperture telescopes, SPIE **3264**, 37 (1998).
6. Robert Q. Fugate, Craig A. Denman, Paul D. Hillman, Gerald T. Moore, John M. Telle, Imelda A. De La Rue, Jack D. Drummond and James M. Spinhirne, “Progress toward a 50-watt facility-class sodium guidestar pump laser,” SPIE **5490**, 1010-1020 (2004).
7. G. T. Moore, “Resonant sum-frequency generation,” IEEE J. Quantum Electron. **38**, 12-18 (2002).