Narrowband, tunable, frequency-doubled, erbium-doped fiber-amplifed transmitter

Mark Stephen,[1,*] Michael Krainak,[1] Haris Riris,[1] and Graham R. Allan[2]

[1]*NASA's Goddard Space Flight Center, Laser and Electro-Optics Branch, Greenbelt, Maryland 20771, USA*
[2]*Sigma Space Corporation, Lanham, Maryland 20706, USA*
**Corresponding author: mark.a.stephen@nasa.gov*

Received February 8, 2007; accepted April 10, 2007;
posted May 21, 2007 (Doc. ID 79957); published July 16, 2007

We report on the development of a fiber-based laser transmitter designed for active remote sensing spectroscopy. The transmitter uses a master oscillator power amplifier (MOPA) configuration with a distributed feedback diode-laser master oscillator and an erbium-doped fiber amplifier. The output from the MOPA is frequency-doubled with a periodically poled potassium titanium oxide phosphate crystal. With 35 W of single-frequency peak optical pump power, 8 W of frequency-doubled peak power was achieved. The utility of this single-frequency, wavelength tunable, power scalable laser was then demonstrated in a spectroscopic measurement of diatomic oxygen A band. © 2007 Optical Society of America

OCIS codes: 140.3460, 300.6360, 140.3600, 140.03500, 140.3280, 280.0280.

We report on the development of a frequency-doubled fiber transmitter that has a high-power, wavelength tunability, and narrow (transform-limited) linewidth capable of making remote measurements of atmospheric temperature and pressure in the near IR. Remote measurements of these atmospheric parameters are required for a number of scientific applications, including weather prediction, climate modeling, and error correction in dynamic gravity field measurements. In addition, applications that require tunable, high-power laser sources at this wavelength include rubidium-based laser cooling and Bose–Einstein condensation experiments [1]. Our architecture capitalizes on several recent advances in fiber amplifiers and makes active laser-based remote sensing instruments practical for space-based instruments.

Laser spectroscopy of the diatomic oxygen A band in the range from 760 to 770 nm can be used to determine atmospheric pressure and temperature from their effect on the shape and strength of the A band absorption lines. The oxygen absorption linewidth at standard temperature and pressure is in the range of a few gigahertz, so high precision (fractions of a percent) measurement of the lineshape and strength is possible with a laser whose linewidth and stability is less than 10 MHz. This measurement concept has been previously demonstrated through active [2–5] and passive [6] spectroscopy. Limitations in previous laser transmitters have hindered practical instrument development. The advent of fiber amplifiers with low mass, volume, and high efficiency now enables feasible laser-based transmitters for active remote sensing from orbiting platforms. We are developing an active laser spectrometer for remote sensing applications. To that end, we have assembled a small, lightweight, efficient laser transmitter capable of high-power, tunable, narrow frequency operation for oxygen spectroscopy. We show that the linewidth is unaffected by amplification, and the system has excellent sideband suppression. We also characterize the frequency-doubling and comment on ways of increasing the doubling efficiency. We describe and characterize the system components, seed laser, fiber amplifier, and frequency doubler, and then discuss the results and limitations of this approach such as stimulated Brillouin scattering (SBS), finally making some preliminary O_2 measurements in a cell.

The laser transmitter consists of an externally modulated, tunable, single-frequency distributed feedback (DFB) laser fiber coupled to an erbium-doped fiber amplifier (EDFA), the output of which is free space coupled and frequency-doubled with a commercial periodically poled potassium titanium oxide phosphate (PPKTP) crystal (see Fig. 1). The output of the C-band EDFA in the 1535–1540 nm region is frequency-doubled to reach the high wavelength end of the oxygen A band [767.5–770 nm].

The DFB seed laser (Furukawa FOL15DCWD series) has been developed in the telecommunications industry and has tunable, narrow frequency emission. It is packaged and fiber coupled with polarization maintaining (PM) fiber and temperature-controlled using an on-chip thermoelectric cooler. The wavelength is dependent on both the temperature (91.8 pm/°C) and the drive current (3.35 pm/mA). Therefore, coarse wavelength adjustment can be achieved with temperature tuning and finer, faster adjustment with current tuning. The spectrum is measured with both a high-finesse fiber Fabry–Perot (FFP) and an optical grating spectrometer. The FFP

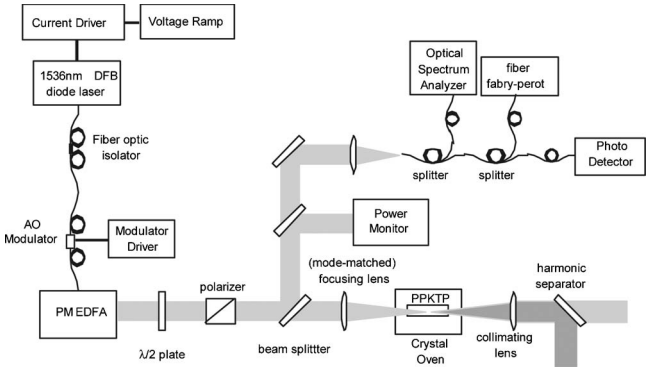

Fig. 1. Diagram of laser setup including DFB seed laser, 2 W average power EDFA, PPKTP, and diagnostics.

 © 2007 Optical Society of America

is a piezolelectric-transducer (PZT)-scanned Fabry–Perot for spectral width measurement. Using the sidebands of a 3 MHz (external) modulation signal to calibrate the FFP measurement, we make an instrument-limited measurement of ~1 MHz for the (instantaneous) linewidth. There is an overall drift in the center wavelength over several seconds (due to instability in temperature and current), which makes a time averaged linewidth of ~10 MHz.

The seed laser is fiber coupled through an acousto-optic (AO) modulator (Neos Technologies AOM-26027) into a single-spatial-mode, 2 W (average), PM EDFA (IPG EAD-2K-C). The maximum peak power achieved with the amplifier was 35 W. This output was limited by SBS in the fiber measured by backreflection and high frequency noise on the output pulse. Using 185 ns pulses at a 250 kHz pulsed repetition frequency and 4.6% duty cycle allowed high peak power and minimal pulse distortion during amplification. The pulsed and amplified signal maintained the narrow DFB linewidth and achieved a sideband suppression ratio (SBSR) of 40 dB. This large suppression of amplified spontaneous emisson and other sidemodes makes this a spectrally pure source, which is ideal for high precision spectroscopy. A side benefit of frequency-doubling is that it further improves the SBSR because of the square dependence on pump power.

The output of the fiber amplifier was collimated into a 5 mm beam diameter, which is then directed through a half-wave plate and polarizer to align the polarization with the doubling crystal. We use a 150 mm focal length lens to focus the light into the PPKTP crystal (Raicol Crystals Ltd.). This corresponds to a calculated spot diameter of 92 μm and a Rayleigh range of 34 mm. The crystal is 30 mm $\times$ 2 mm $\times$ 1 mm and is temperature controlled for optimum doubling efficiency. Using the laser wavelength, λ, the crystal length, L, the beam waist, ω_0 and the index of refraction for the fundamental wavelength, n_ω, we use the equation

$$\xi = \frac{\lambda L}{2\pi\omega_0^2 n_\omega} \tag{1}$$

to calculate a Boyd–Kleinman [7] confocal focusing parameter, ξ, of 0.47. Various other single lenses and double lens combinations were tried to optimize doubling but did not yield better results.

With 35 W of fundamental, peak optical power, over 8 W of frequency-doubled peak optical power was achieved with 23% conversion efficiency. The data are shown in Fig. 2. Higher peak powers and conversion efficiencies can be achieved with shorter pulses (~1 ns), which raises the SBS threshold [8,9], however shorter pulses will broaden the laser spectrum to an unacceptable degree for our application. Higher peak power, single-frequency amplifiers have recently been developed so the results here can be scaled to higher powers and increased conversion efficiency [10–12].

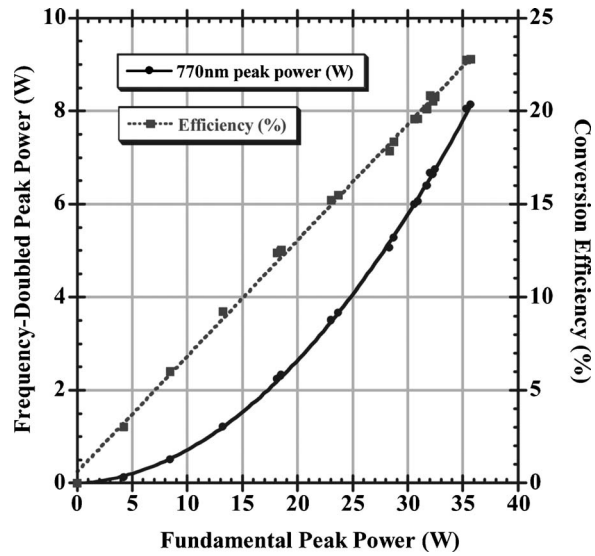

Fig. 2. Frequency-converted power and efficiency with changing pump power using 185 ns pulses with a 250 kHz repetition frequency.

Using the fundamental power, P_ω, the doubled power, $P_{2\omega}$, and the crystal length, L, we use the equation

$$\eta = \frac{P_{2\omega}}{LP_\omega^2} \tag{2}$$

to calculate the normalized efficiency, η. We then use the optical frequency, ω, the permittivity of free space, ε_0, the speed of light, c, the index at the doubled frequency, $n_{2\omega}$, and the equation

$$d_{\text{eff}} = \left(\frac{\eta\pi n_\omega n_{2\omega}\varepsilon_0 c^4}{2\omega^3\xi}\right)^{1/2} \tag{3}$$

to calculate the effective nonlinear index of the crystal, d_{eff}, to be 8 pm/V. This is nearly a factor of 2 smaller than other reported values [13,14].

The PPKTP temperature was tuned over a wide range and shows some asymmetry in the theoretically predicted sinc-squared function (see Fig. 3). If the poling period were not exactly maintained over the entire 30 mm, this could account for the less than optimum conversion efficiency, meaning the d_{eff} calculated is accurate for this crystal, despite its variance with other published values. Increased doubling efficiency may be achieved with a better poled PPKTP crystal or a shorter length of crystal, over which the poling can be maintained.

The doubled output was then aligned through an asymmetric 334-bounce Herriot cell to achieve the desired 295 m path length. The time-of-flight was measured to ensure the beam was aligned properly and achieving the desired path length. The DFB wavelength was tuned through an oxygen line at 768.5 nm (1537 nm at fundamental) by ramping the laser current. Although the current modulation also changes the output power of the DFB, the amplifier is saturated so there is little change in the output power after amplification. The laser was then

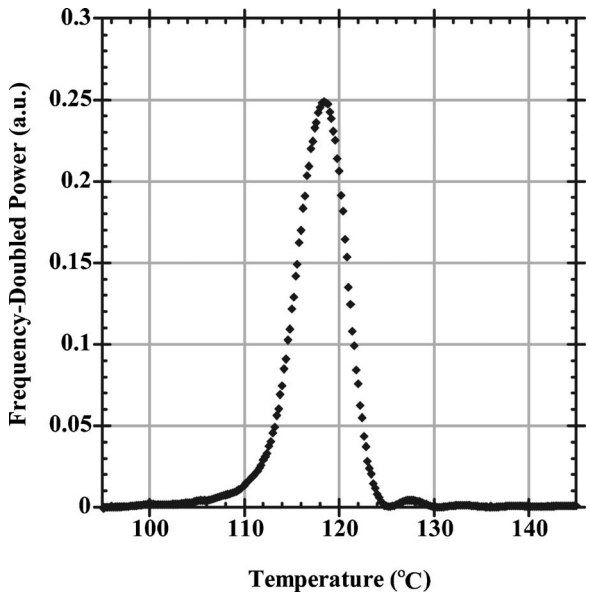

Fig. 3. Measured temperature dependence of the frequency-doubling signal under cw illumination. This crystal shows some asymmetry and smaller than expected sidelobes. A perfectly poled crystal should have a sinc-squared functional form.

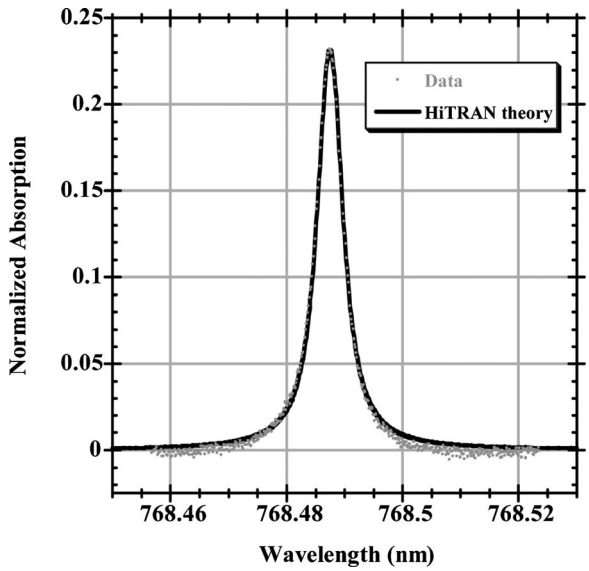

Fig. 4. Wavelength scan of oxygen line through a 295 m path overlayed with theory from the HITRAN database [15].

scanned (using current modulation at ~200 Hz) through an oxygen line and the transmission was measured. This scan was >120 pm in the fundamental and >60 pm at the doubled frequency. In addition, external AO modulation (at ~300 kHz) is continued to maintain high peak optical power and doubling efficiency. We use a beam splitter directly before entrance to the cell as a reference to monitor the transmitted power. The detectors are connected to a digital acquisition board, and the power transmitted through the cell is then divided by the reference (point-by-point) and normalized to get an accurate measurement of the oxygen absorption. Results of these measurements are shown in Fig. 4. The wavelength scale was created by calculating the DFB current tuning and measuring the ramp voltage. The center wavelength was adjusted to match the expected result. The measured linewidth agrees very well with the HITRAN [15] database.

The development of a scalable, high-power, frequency-doubled fiber transmitter that has wavelength tunability and a narrow (transform-limited) linewidth shows great promise in active remote sensing spectroscopy. We have shown that this system can measure the line shape of the oxygen absorption with no degradation in lineshape. This particular architecture capitalizes on recent advances in fiber amplifiers and makes laser-based remote sensing instruments feasible for space-based instruments. Ongoing improvements in EDFA design, such as higher SBS threshold will yield higher efficiency and peak powers.

References

1. R. J. Thompson, M. Tu, D. C. Aveline, N. Lundblad, and L. Maleki, Opt. Express **11**, 1709–1713 (2003).
2. C. L. Korb and C. Y. Wang, Appl. Opt. **22**, 3759 (1983).
3. K. J. Ritter, Ph.D. dissertation submitted to the University of Maryland Graduate School (1986).
4. G. K. Schwemmer, M. Dombrowski, C. L. Korb, J. Milrod, H. Walden, and R. H. Kagann, Rev. Sci. Instrum. **58**, 2226 (1987).
5. C. N. Flamant, G. K. Schwemmer, C. L. Korb, K. D. Evans, and S. P. Palm, J. Atmos. Ocean. Technol. **16**, 561 (1999).
6. E. Georgieva, E. Wilson, M. Miodek, and W. Heaps, Opt. Eng. **45**, 115001 (2006).
7. G. D. Boyd and D. A. Kleinman, J. Appl. Phys. **39**, 3597 (1968).
8. G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic, 2001).
9. P. A. Champert, S. V. Popov, and J. R. Taylor, Electron. Lett. **37**, 1127 (2001).
10. Y. Jeong, J. K. Sahu, D. B. S. Soh, C. A. Codemard, and J. Nilson, in *Optical Fiber Communications Conference* (Optical Society of America, 2005), postdeadline paper PDP1.
11. D. V. Gapontsev, O. Shkurikhin, and N. Platonov, presented at the 3rd International Symposium on High-Power Fiber Lasers and Their Applications, St. Petersburg, Russia, July 1–3, 2006.
12. M. Y. Vyatkin, A. C. Dronov, M. A. Chernikov, S. V. Popov, J. R. Taylor, D. V. Gapontsev, and V. P. Gapontsev, in *Conference on Lasers and Electro-Optics, 2005 (CLEO)* (Optical Society of America, 2005), Vol. 3, pp. 1993–1994.
13. P. A. Champert, S. V. Popov, and J. R. Taylor, Appl. Phys. Lett. **78**, 2420 (2001).
14. A. Englander, R. Lavi, M. Katz, M. Oron, D. Eger, E. Lebiush, G. Roseman, and A. Skliar, Opt. Lett. **22**, 1598 (1997).
15. L. S. Rothman, D. Jacquemart, A. Barbe, D. C. Benner, M. Birk, L. R. Brown, M. R. Carleer, C. Chackerian, K. Chance, L. H. Coudert, V. Dana, V. M. Devi, J. M. Flaud, R. Gamache, A. Goldman, J. M. Hartmann, K. W. Jucks, A. G. Maki, J. Y. Mandin, S. T. Massie, J. Orphal, A. Perrin, C. P. Rinsland, M. A. H. Smith, J. Tennyson, R. N. Tolchenov, R. A. Toth, J. Vander Auwera, P. Varanasi, and G. Wagner, J. Quant. Spectrosc. Radiat. Transf. **96**, 139 (2005).