Iodine stabilization of a diode laser in the optical communication band

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The iodine molecule has frequently been used as a frequency reference from the green to the near-infrared wavelength region (500–900 nm). We describe the frequency locking of the second-harmonic signal of a 197.2-THz (1520.25-nm) distributed-feedback diode laser to the absorption lines of the iodine hyperfine structure; a frequency jitter below 0.1 MHz was achieved at a 300-ms time constant. This scheme provides a simple, compact, and high-performance frequency reference in the optical communication band. © 2005 Optical Society of America

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The iodine molecule has frequently been chosen as a frequency reference for calibration purposes and laser spectroscopic applications in a broad region of the optical spectrum from the green to the near infrared (500–900 nm). Nearly 100,000 Doppler-broadened transitions have been calibrated by Fourier-transform spectroscopy covering this range and published in Refs. 1–3. However, for frequency references with cw lasers that have typical bandwidths of 1 MHz, the accuracy provided by Doppler-broadened lines is insufficient. High frequency stability is achieved by use of sub-Doppler techniques such as saturation spectroscopy for locking to an atomic or molecular transition; this permits stabilization even of hyperfine components with a homogeneous spectral width at the megahertz level. Extending the range of frequency references based on the iodine spectrum is possible by use of a nonlinear optical interaction, such as the most commonly used second-harmonic generation (SHG). It can therefore provide optical frequency references in the region 1000–1800 nm, including the telecommunication band. Studies of frequency references that combine SHG and transitions of the ^{39}K (Refs. 4 and 5) and Rb (Refs. 6–9) atoms have demonstrated high stability, but the choices of frequency reference are still limited to a finite number of atomic transitions.

In 2000, Cheng *et al.* successfully resolved the rovibronic transitions of the iodine molecule, using SHG of a 1534-nm diode laser.[10] In 2002, Klein and Arie reported the application of wavelength references to iodine transitions[11] to dense wavelength-division-multiplexed systems and related instrumentation. The lowest limit of saturation power that permitted sub-Doppler observation was 1.5 mW. The recent development of highly efficient reverse proton exchanged waveguides in a periodically poled lithium niobate (PPLN) waveguide[12] permitted efficient extraction of more than 10 mW of second-harmonic (SH) power from 100-mW pump power in the telecommunication band. That was more than 10% conversion efficiency without any enhancement cavity. Such high power of the SH is enough for iodine saturation spectroscopy to reveal the hyperfine structure of iodine in the 760-nm region and enables the laser frequency to be locked to a sub-Doppler linewidth. In this Letter we report the demonstration of frequency locking by use of the scheme mentioned above, with only one laser.

The experimental setup is shown in Fig. 1. The laser source was a commercial distributed-feedback diode laser (NLD1556STG, NTT Electronics). Its central frequency was 197.2 THz and its linewidth was less than 2 MHz (according to the manufacturer's data sheet). We could tune the laser's wavelength by varying the operation temperature (0.11 nm/°C) and the laser-driven current (5.84 pm/mA). The 20-mW output power of the distributed-feedback laser was amplified to 100 mW by an erbium-doped fiber amplifier (Technology Thesaurus Company). A fiber polarization controller rotated the laser polarization direction at the fiber output to be parallel to the extraordinary direction of the PPLN waveguide. The beam size was adjusted by an optical telescope for op-

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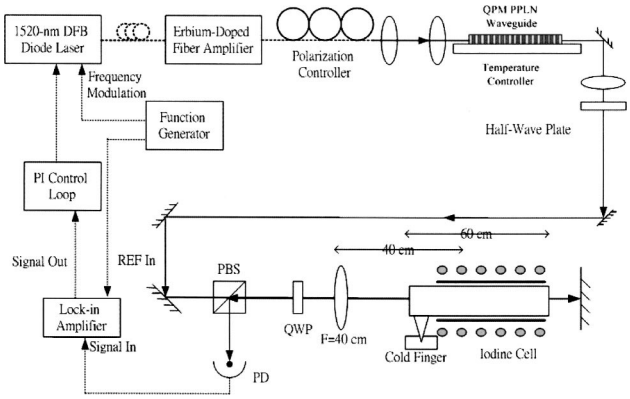

Fig. 1. Experimental setup: PBS, polarizing beam splitter; PD, photodetector; QWP, quarter-wave plate; PI, proportional-integral; QPM, quasi-phase matched; REF, reference.

timal coupling into the waveguide. The temperature of the waveguide device was normally kept at 106.5 °C by a temperature controller (Lakeshore 340) to meet the quasi-phase-matching condition and also to reduce the photorefractive effect. The photorefractive effect caused a noticeable fluctuation of SH power at lower temperature. The temperature instability was kept within 0.01 °C to eliminate SHG power fluctuation. The optical power of the SH signal was typically 15 mW. After the PPLN waveguide, an $f=25$ mm plano–convex lens was used to collimate the SH beam. The collimated beam's size was 0.5 mm.

The PPLN waveguides used in the experiment were 52 mm long and had a 46-mm poling region and 1.5-mm-long mode filters (single-mode waveguide segments) and tapers on each side. Mode filter widths ranging from 3 to 6 μm were used to permit flexibility in mode matching of the input and output of the waveguides. The poling period was 15 μm, with a duty cycle of 50±5%. The reverse proton exchange method was used for fabrication.[10] The periodically poled chip was proton exchanged in benzoic acid at 160 °C for 23.8 h to a depth of 1.22 μm and then annealed in air at 312 °C for 19.9 h and reverse proton exchanged in a eutectic melt of lithium nitrate, sodium nitrate, and potassium nitrate at 301 °C for 21.7 h.[13] The typical internal SHG conversion efficiency of the waveguides was in the range $(90-100)\%/\mathrm{W\,cm^2}$, with propagation losses of 0.27–0.4 dB/cm. Noncritical phase matching was obtained for a waveguide width of 6.5 μm. The phase-matching wavelength at room temperature was 1508.7 nm.

The iodine cell was 60 cm long and was heated to 600 °C to increase the optical absorption by raising the population of the lower state. The temperature of the cold finger was kept at 27 °C to control the gas pressure in the cell at 49 Pa to prevent pressure broadening. The 15-mW SH beam was focused at the middle of the cell by an antireflection-coated lens with $f=40$ cm. The horizontal linear polarization direction was converted to circular polarization by a quarter-wave plate before directing the beam into the cell. The transmitted beam was reflected back into the cell by a mirror. The circular polarization was converted to vertical linear polarization after it passed through the quarter-wave plate again. It was then reflected by a polarizing beam splitter to a photodetector (New Focus 2001).

The Doppler-broadened iodine spectrum was observed at 1-mW SH power by the amplitude modulation technique with an optical chopper. The transition was identified as the $R(55)$ 1–13 transition. Its Doppler linewidth was 1.2 GHz, and its linear absorption contrast was 1.2×10^{-3}. The 13 155.64-$\mathrm{cm^{-1}}$ wave number of this transition measured with a Burleigh WA-1000 wavemeter (0.02-$\mathrm{cm^{-1}}$ accuracy) was in good agreement with the 13 155.646-$\mathrm{cm^{-1}}$ value given in the iodine atlas.[1] Doppler-free collinear saturation spectroscopy was then used to resolve the hyperfine components of the rovibronic transitions of the iodine molecule. The laser was current-modulated at $f_{\mathrm{mod}}=25$ kHz with a 15-MHz modulation depth at the SH signal. The signal from the photodetector was demodulated with a lock-in amplifier at the third-harmonic frequency. A typical spectrum of the demodulated signal at the third harmonic of the modulation frequency is shown in Fig. 2, in which the sub-Doppler spectrum can easily be identified. The scan range was 800 MHz. The hyperfine transitions shown in Fig. 2 were identified as the a_1–a_{21} components of the $R(55)$ 1–13 transition. The signal-to-noise ratio was larger than 70 at a 300-ms time constant. The third-harmonic demodulated signal was a zero-crossing signal that we used to lock the laser frequency on the iodine saturation absorption line centers. The demodulated signal was fed into the proportional-integral control loop to control the current of the distributed-feedback diode laser. Although the individual hyperfine components were not completely resolved because of pressure broadening and a large frequency modulation depth, the zero-crossing signal could still be used to stabilize the laser frequency to a submegahertz level. As there are no peaks near the a_{18} component in the higher-frequency side, we chose that component to provide the locking signal for laser frequency stabilization. A time trace of the error signal when the laser was locked is shown in Fig. 3. The time constant of the lock-in amplifier was 300 ms. From the locked error

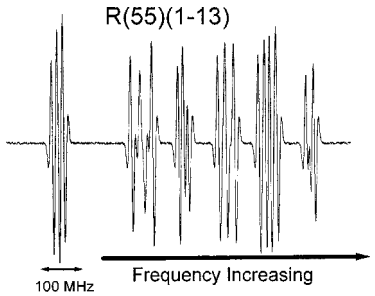

Fig. 2. Third-harmonic demodulated saturated-absorption spectrum. The hyperfine structure of iodine is identified as a_1–a_{21} components of the $R(55)$ 1–13 transition. The signal-to-noise ratio is greater than 70 at a 300-ms time constant.

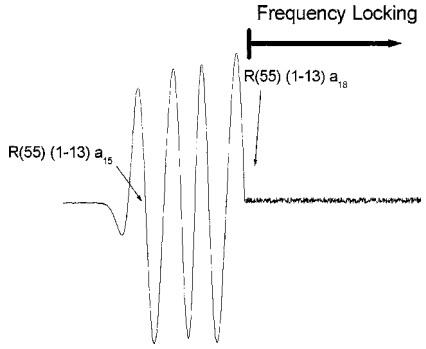

Fig. 3. Typical trace of the third-harmonic demodulated signal of the laser locked to the a_{18} component. Modulation depth, 15 MHz; the modulation frequency, 25 kHz.

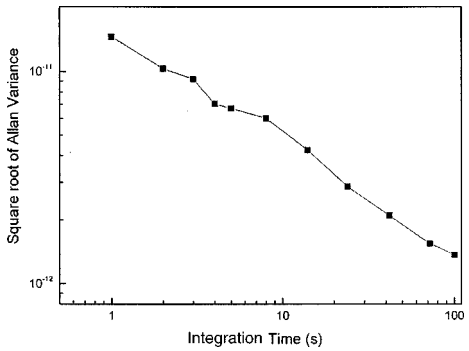

Fig. 4. Square root of Allan variance as a function of measurement time.

signal, the peak-to-peak frequency jitter was estimated to be 0.2 MHz at 760.1 nm. This means that the laser frequency at 1520 nm was frequency stabilized to within 0.1 MHz. We also used a series of measurements with different measurement times to calculate the square root of the Allan variance, as shown in Fig. 4. The frequency stability estimated from the locked error signal is 5×10^{-12} (10 s), which corresponds to a frequency variation of 1 kHz at 1520.2 nm.

In conclusion, for the first time to our knowledge the iodine saturation absorption spectrum was observed by use of a light source from a PPLN waveguide pumped by an erbium-doped fiber amplified external cavity diode laser. The efficient SHG conversion leads to a good signal-to-noise ratio and permits direct locking of the laser frequency to the saturation absorption line of the iodine hyperfine structure transition. The compact experimental scheme eliminates the need for an enhancement cavity[8] or laser power amplification.[9] Therefore, secondary frequency references for dense wavelength-division multiplexed systems can be achieved with an iodine-stabilized laser. Because the iodine molecule has dense absorption lines, this scheme can provide a feasible, compact frequency reference system for dense wavelength-division multiplexed applications for all-optical communication bands.

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