Development of Absolute Frequency Reference at 1064 nm for Coherent Transmission and Laser Drift Measurements

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Abstract:
By stabilizing a laser on the flank of a Doppler broadened iodine absorption line, a test bed to measure the frequency stability performance of potential coherent communications lasers has been developed. The system can also be used to provide a compact platform for laser frequency stabilization for use in free space coherent laser communications. The reproducible absolute frequency accuracy is better than 2.3×10^{-8}. The effects of temperature on system accuracy and drift measurements of a communications laser are also presented.

Introduction:
The Transmission Technology branch in the Institute for Communications Technology of the German Aerospace Center is investigating free space optical homodyne communications links using 1064 nm Nd:YAG lasers. For a coherent optical communications system, a tunable absolute frequency reference has tremendous benefits. Typical lasers being used for communications systems exhibit temperature drift and frequency uncertainties of several GHz over the required lifetime of a space-based optical communication system. A communication system where each laser is stabilized to a known frequency reference has the obvious benefits of requiring far less time to initiate a communications link while eliminating the need for complex frequency acquisition algorithms. Another benefit is a frequency multiplexing capability by locking lasers on different absorption lines of a reference medium. At 1064 nm molecular cesium can be used as a frequency standard [1]. However, cesium absorption at room temperature is poor, heating is required to obtain a sufficient signal to noise ratio and special handling procedures are required, which combine to make it a poor choice as an absolute reference. A well characterized frequency reference, iodine gas, is available at the second harmonic of 1064 nm. Previous efforts have focused on locking the laser frequency to a dip in an iodine absorption line [2]. However, in order to successfully lock and track on an absorption dip the laser must be frequency modulated well above the proposed stabilization loop bandwidth. Since, with a coherent communications system, data is normally frequency or phase modulated, additional modulation of the signal would make reconstructing the data at the receiver more complex. An absolute reference can still be obtained by stabilizing the laser on a flank of an Doppler broadened iodine line. This was initially accomplished at DLR by Heilmann and Kuschel [3]. This work builds on the previous efforts at DLR by digitizing the system, developing an absorption line identification algorithm and increasing system precision and acquisition speed with the addition of nested thermal-piezo control. It culminates in the development of a laser frequency drift measurement test bed.

Experimental Setup:
The experimental setup is shown in figure 1. A potassium titanyl phosphate (KTP) non-linear crystal is used to frequency double the 1064 nm Nd:YAG laser output. The laser light passes through the KTP crystal which outputs green (532 nm) and residual 1064 nm infrared light. A harmonic beam splitter separates the beam into its green and infrared components. One part of the green beam continues on through the iodine cell onto a photo-diode while the other is detected directly. The ratio of these signals varies with the frequency absorption spectrum of the iodine cell. Narrow band pass filters are placed in front of each of the photo diodes to remove extraneous background and any residual 1064 nm light. The digital control outputs are used to drive the temperature and piezo frequency control elements in the laser head. The residual 1064 nm light after the KTP is fed into a fiber optic and mixed with a signal from the laser under test. A balanced frontend receiver provides the intermediate frequency signal which is monitored by a spectrum analyzer. The heating element under the iodine cell is used for temperature testing.

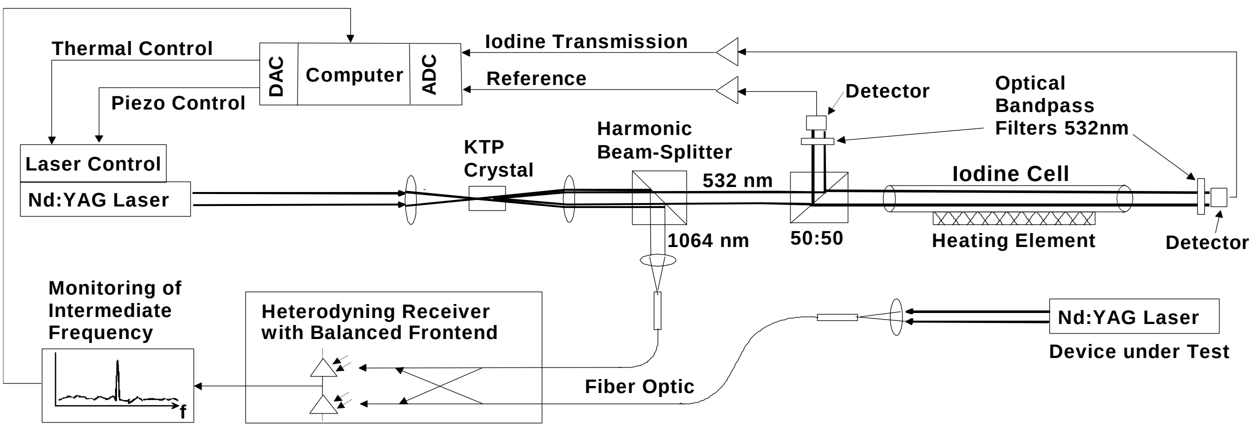

Figure 1. Experimental Setup

System Operation:
The laser thermal controller is driven to scan frequencies within a mono-modal operating regime of the laser. The spectrum is normalized with the reference signal to ensure that fluctuations in laser output power are not factored into control calculations. During the scan, the transmission dips are recorded as a function of the laser thermal input voltages. The absorption lines that exceed a certain threshold and width are identified as peaks. These measured peaks are then compared to those in the iodine reference atlas which provides magnitude information for all the absorption lines (transmission dips) it identifies by number and frequency [4]. The mean square error of the magnitude between the reference and measured spectrum peak magnitudes is calculated. The minimum of this error identifies the correct match. This method works very well when there are at least three absorption lines in the measured data. Once the frequency lines have been identified, a point on the flank on any one of the identified Doppler broadened lines is selected. The computer then uses the thermal input of the laser in an open loop fashion to drive the crystal to the desired absorption line. After achieving the desired Doppler broadened line, the thermal controller is initiated to drive the frequency towards the desired set point on the flank of the line. Once the frequency error is within the piezo field of regard, piezo control is initiated and the thermal controller is now used to null the piezo command voltage. Using this control system the laser can be stabilized on any Doppler broadened line identified during the initial scan. In a system with more than one laser this would enable frequency multiplexing of the communications signal. Two different lasers can be stabilized on different absorption lines, thus always maintaining frequency separation. Additionally, the absorption line flank setpoint can be between 20 to 80% absorption, depending on the iodine line characteristic, enabling a continuous frequency tuning range of about 200 MHz. The system is also capable of stabilizing on either side of a Doppler broadened line.

Results:
All frequency results presented are referenced back to 1064 nm. Figure 2 shows time responses for iodine flank acquisition and stabilization, using line 1107, for the thermal and nested piezo-thermal control designs. Once the loop has been closed, flank acquisition (residual error stays below 1% which is approximately 3.5 MHz) is three times faster with the nested piezo-thermal control loop. The absolute frequency accuracy is a function of the exact location of the desired absorption flank stabilization point. This depends heavily on the incident light energy received by the two photo-detectors. Laser power fluctuations are compensated by the use of the reference diode. However, with the present system 2% errors remain uncompensated resulting in 7 MHz (2.3×10^{-8}) absolute frequency performance repeatability. The relative error, the residual from not being able to track the desired flank set point exactly, is less than 100 kHz. The best possible resolution of the thermal-only control system is limited by the thermal scale factor, the digital system quantization, and the large time lag of the thermal controller inside the laser head to about 500 kHz.

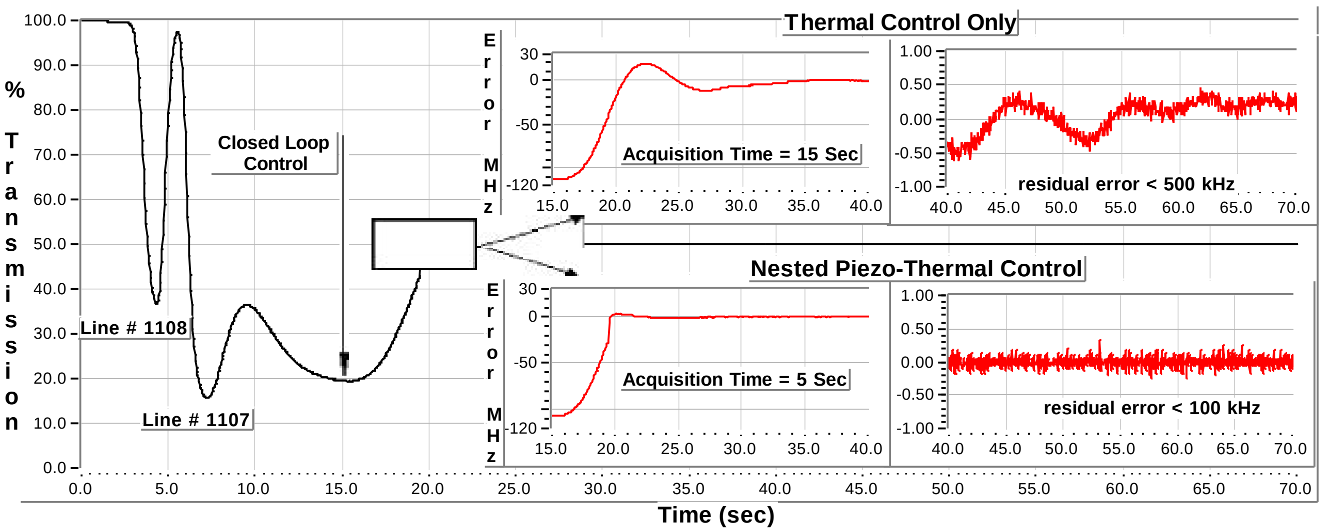

Figure 2. Frequency Acquisition and Stability Results

Temperature Tests:
Temperature changes in the iodine cell effect the shape of the Doppler broadened lines, and hence the frequency performance of the system. All the previous tests were accomplished at room temperature as was the case with the iodine reference atlas [4]. A heating element was used to increase the temperature of the iodine gas which was measured with a sensor attached to the glass of the iodine cell. Lacking another stabilized laser to measure the change in frequency with respect to temperature, the result was obtained using successive sweeps of two closely spaced iodine lines. As is seen in figure 3, the full-width half-maximum (FWHM) frequency of the line has increased with temperature. Using the scale factor of the laser and the consecutive measurements to remove the effects of laser drift, the frequency error resulting from the further broadening of the absorption line can be determined. A measured FWHM change of 1.3 MHz/K indicates a 0.65 MHz/K frequency error.

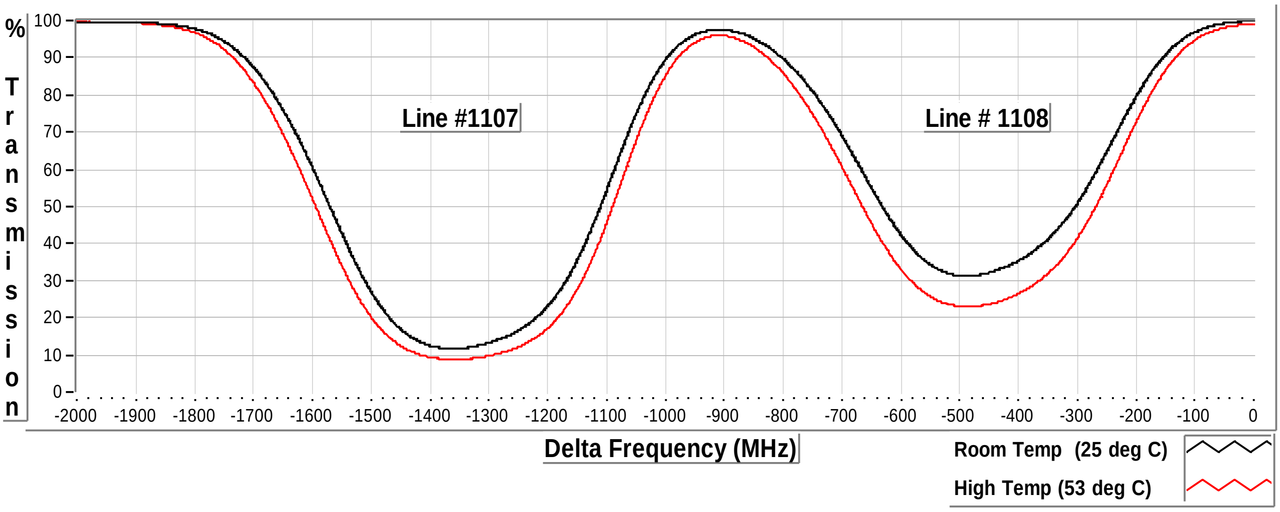

Figure 3. Iodine Absorption Line Temperature Broadening

Drift Test:
Using the heterodyning frontend, setup shown in figure 1, the drift of a laser (device under test) was measured. The frequency stabilized laser was stabilized on the flank of an absorption line and the drift of the test laser was measured over a period of two hours. The results are presented in figure 4.

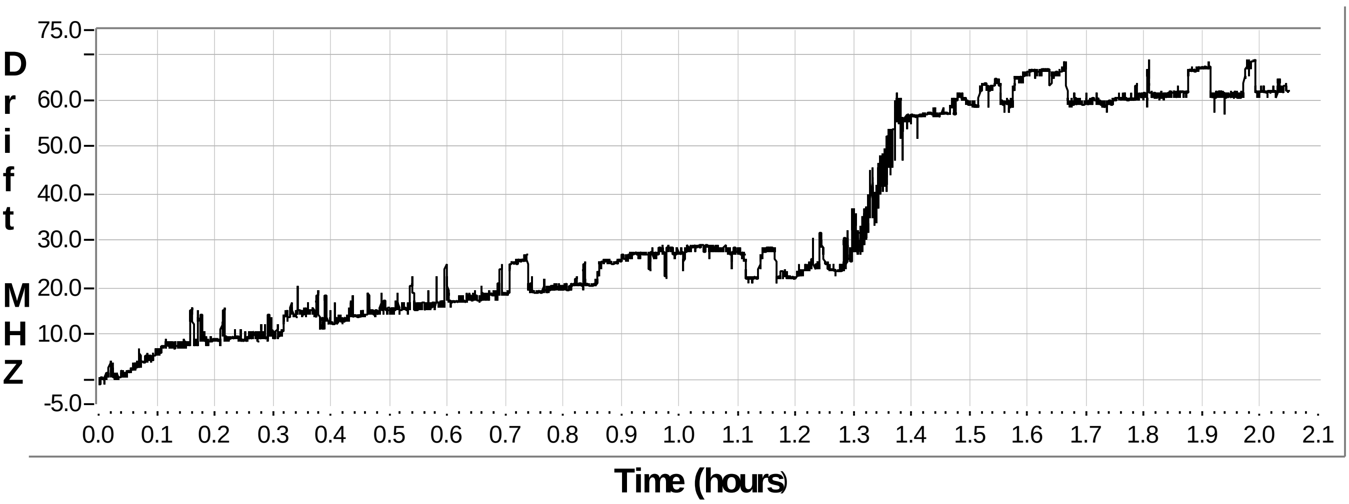

Figure 4. Laser Frequency Drift Measurement

Conclusions:
A simple frequency stabilized laser frequency drift measurement testbed has been developed. The long term repeatable absolute measurement accuracy incorporating nested piezo and thermal laser frequency control is 7 MHz. The system is small, compact and can also be used for frequency stabilization in a free space laser communications system. Frequency multiplexing can be performed by stabilizing separate lasers on different iodine absorption lines, thereby always maintaining frequency separation. A continuous tuning range of about 200 MHz is available at each absorption line. Temperature affects the accuracy of the measurement as each degree change in temperature shifts the frequency about 0.65 MHz. Stabilizing on the flank of a Doppler broadened iodine line eliminates the need for modulation and provides enough accuracy so that this system can be used as a measurement testbed and modified into a frequency stabilization platform to be used to speed up and simplify frequency acquisition for a coherent optical communications system.

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