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Widely tunable laser frequency offset lock with 30 GHz range and 5 THz offset

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Abstract: We demonstrate a simple and versatile method to greatly extend the tuning range of optical frequency shifting devices, such as acousto-optic modulators (AOMs). We use this method to stabilize the frequency of a tunable narrow-band continuous-wave (CW) laser to a transmission maximum of an external Fabry-Perot interferometer (FPI) with a tunable frequency offset. This is achieved through a servo loop which contains an in-loop AOM for simple radiofrequency (RF) tuning of the optical frequency over the full 30 GHz mode-hop-free tuning range of the CW laser. By stabilizing the length of the FPI to a stabilized helium-neon (HeNe) laser (at 5 THz offset from the tunable laser) we simultaneously transfer the ~ 1 MHz absolute frequency stability of the HeNe laser to the entire 30 GHz range of the tunable laser. Thus, our method allows simple, wide-range, fast and reproducible optical frequency tuning and absolute optical frequency measurements through RF electronics, which is here demonstrated by repeatedly recording a 27-GHz-wide molecular iodine spectrum at scan rates up to 500 MHz/s. General technical aspects that determine the performance of the method are discussed in detail.

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1. Introduction

Narrowband continuous-wave (CW) stabilized lasers have many applications in experimental atomic and molecular physics, examples including laser spectroscopy, laser cooling, and coherent optical manipulation of atoms and molecules. Such experiments often require wide optical frequency tunability, as well as precise control of the absolute optical frequency. A commonly-used method is to lock a laser source directly to a nearby optical or molecular reference transition, after which part of the laser output is sent through a variable-frequency-shifting device such as an acousto-optic modulator (AOM) or an electro-optic modulator (EOM). Both AOMs and EOMs have the practical advantage that optical frequency tuning is readily accomplished by adjusting the radio frequency (RF) of the device driver electronics. The frequency shift of AOMs is restricted to typically 1 GHz by the limited phase velocity of the acoustic wave in the acousto-optic crystal, while the tuning range is limited to a fraction of the shift (typically 50–100 MHz). In addition, the diffraction efficiency of AOMs tends to decrease with increasing RF frequency. Frequency shifting over larger ranges while maintaining high efficiencies is possible using EOMs. For example, employing serrrodyne phase modulation, continuous tuning over 1.5 GHz of a stabilized optical frequency was achieved with an efficiency of over 80% [1, 2]. Frequency shifting over ± 32.5 GHz with an efficiency of 60% was achieved with a technique based on cascaded electro-optical traveling phase gratings in a traveling wave EOM [3]. An alternative method is to offset lock a slave laser to a master laser by detecting their beat note with a fast photodiode and stabilizing the beat-note frequency to the output of a microwave synthesizer [4, 5]. This method is limited by the detection bandwidth of the photodiode, which may reach up to 100 GHz. A practical disadvantage of the latter two methods is the need for spectrally pure, high-end microwave oscillators.

For optical frequency offset locking and tuning at larger detunings, so-called transfer cavities are often used [6]. Here the length of a Fabry-Pérot interferometer (FPI) is stabilized to the wavelength of a first laser, which is locked to an atomic or molecular reference transition. A second 'spectroscopy' laser is subsequently locked to one of the transmission maxima of the cavity, thereby allowing for frequency offsets in the many-THz range. However, the continuous tuning range remains limited by the AOM or EOM needed for frequency shifting from the reference cavity mode. A similar method employs an optical frequency comb laser [7]: here, the spectroscopy laser is locked to a nearby mode of the comb spectrum, for instance by stabilizing the optical beat-note frequency to a tunable RF reference frequency.

Tunable lasers with known frequencies are also of interest to laser spectroscopy. Here, fre-

frequency calibration is often achieved by use of an FPI locked to an atomic or molecular reference frequency, where the free spectral range (FSR) of the FPI is calibrated against two well-known atomic or molecular reference lines [8]. Thus, as the spectroscopy laser is scanned over the spectrum of interest the FPI transmission maxima provide a relative frequency scale. This approach is limited by nonlinear scanning of the spectroscopy laser and interpolation errors in between the FPI transmission maxima.

In this paper, we present a simple and generally applicable RF method to tune optical frequencies over frequency ranges in excess of 25 GHz, and at frequency offsets of several THz from an atomic or molecular reference line. The method combines a transfer cavity, locked to a frequency-stabilized helium-neon (HeNe) laser, with an AOM that is placed inside the servo loop that locks the spectroscopy laser to the transfer cavity. With this method we demonstrate tuning at 500 MHz/s of a narrowband CW laser over its mode-hop-free tuning range of ~ 30 GHz while maintaining reference to the HeNe laser. Furthermore, the absolute optical frequency of the laser can be set with a reproducibility of 1 MHz anywhere in its 30-GHz tuning range. Our method also circumvents nonlinear scanning issues and the need for interpolation in between transmission maxima for laser spectroscopy. To verify the frequency reproducibility and to illustrate the general applicability of the method, we demonstrate spectroscopy of a 27-GHz-wide portion of the spectrum of molecular iodine (I_2).

2. Experimental setup and principle of operation

Figure 1 depicts our experimental setup. A central role is played by the FPI which here acts as a transfer cavity. The FPI has a length of 0.5 m and is stabilized to the wavelength of a CW 632.8 nm helium-neon laser as follows. The output of the HeNe laser is coupled into the FPI, and the transmitted power is detected by a first photodiode (PD1). One of the FPI mirrors is mounted onto a piezo-ceramic actuator (PZT), driven by a sinusoidal voltage with frequency $f_M = 735$ Hz. The resulting cavity-length modulation dithers the transmitted power at PD1, which is converted into an error signal using a lock-in amplifier. The choice of f_M is a compromise between high detection bandwidth and the limited response time of the PZT. The error signal is fed into a servo loop with PI characteristic which provides feedback to the PZT to control the FPI length for maximum HeNe transmission. In this way, the 1 MHz long-term frequency accuracy of the HeNe laser is transferred to the length of the FPI. All experiments described below were conducted with the HeNe servo loop closed.

In our setup, the FPI serves to stabilize the wavelength of a second CW laser, which is a commercial ring dye laser running on sulforhodamine B near 626 nm. This laser is used for various purposes, as discussed in more detail in Sec. 3. The dye laser frequency is locked to the FPI as follows. A small portion (0.5%) of the dye laser output is picked off and sent through an AOM. Operating the AOM in double-pass configuration [9] allows shifting the optical frequency by an amount $\Delta_{\text{AOM}} = 500 \pm 100$ MHz, without significantly affecting the propagation direction of the doubly-diffracted output beam. The AOM is driven by a voltage-controlled oscillator (VCO), whose output is amplified to 1.5 W. The double-pass diffraction efficiency of the AOM varies between 0.2 and 0.7 over the entire tuning range. The doubly-diffracted beam is subsequently overlapped with the HeNe laser beam using a polarizing beamsplitter cube (PBC), and coupled into the FPI. Care is taken to excite only the TEM_{00} transverse mode of the FPI. After the transmission, the dye laser light is separated from the HeNe light by a second PBC, and detected by a second photodiode (PD2). Due to the modulation of the FPI length through the PZT, the transmission signal at PD2 is modulated at frequency f_M as well. This signal is fed into a second lock-in amplifier which delivers an error signal to a second PI servo loop. The latter provides feedback to the external scan input of the dye laser's control electronics. Thus, the wavelength of the output of the double-pass AOM is locked to the length of the FPI.

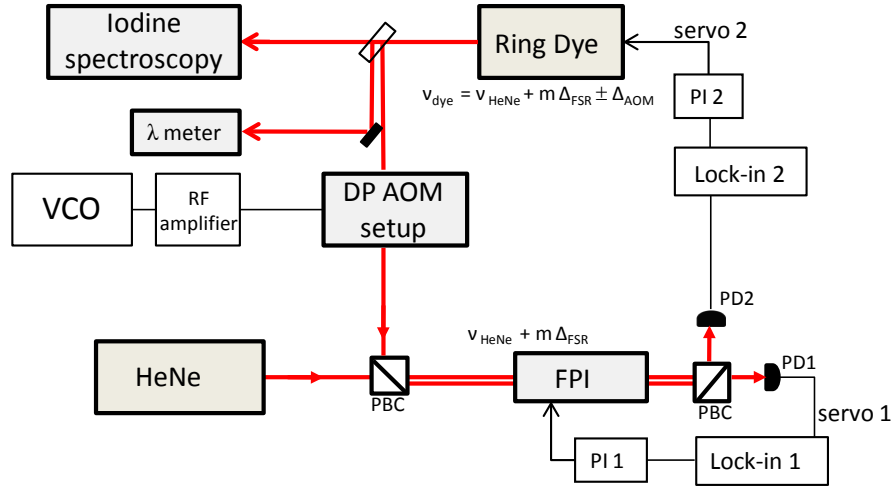


Fig. 1. Experimental setup scheme. Red lines indicate optical beam paths, whereas electrical connections are colored black. VCO, Voltage Controlled Oscillator; DP AOM, double-pass AOM setup; PI, proportional-integral loop filter; lock-in, lock-in amplifier; PD, photodiode; PBC, polarizing beamsplitter cube; λ meter, optical wavelength meter. The overlapped laser beams traveling through the FPI are offset here for clarity.

The in-loop AOM may be used to tune the frequency of the dye laser over an arbitrary range with respect to the HeNe laser frequency as follows. First, we note that the output frequency of the dye laser, ν_{dye} , and the frequency of HeNe laser, ν_{HeNe} , are related via

$$\nu_{\text{dye}} = \nu_{\text{HeNe}} + m\Delta_{\text{FSR}} \pm \Delta_{\text{AOM}}, \quad (1)$$

where m is an integer which corresponds to the number of FPI modes separating ν_{dye} from ν_{HeNe} , and $\Delta_{\text{FSR}} \simeq 149$ MHz stands for the FSR. The absolute values of ν_{HeNe} and m do not have to be known in order to operate the system and use this method. As will become clear below, it is essential that the 200 MHz tuning range of the double-pass AOM setup exceeds the FSR of the FPI.

If the AOM frequency is tuned slowly (*i.e.* much slower than the control bandwidth of the dye laser servo loop), the servo loop will act so as to maintain the condition expressed by Eq. (1). This allows tuning ν_{dye} by 200 MHz with respect to the fixed mode frequencies of the FPI, as depicted schematically in Fig. 2(a). By contrast, if the AOM frequency is tuned rapidly (*i.e.* much faster than the response time of the dye laser servo loop) by exactly one FSR of the FPI, this sudden ‘jump’ in AOM frequency will not be detected by the servo loop, and the dye laser frequency will not be affected. In effect, the lock will be re-established at the next mode of the FPI so that the frequency of the dye laser can now be written

$$\nu'_{\text{dye}} = \nu_{\text{HeNe}} + (m \pm 1)\Delta_{\text{FSR}} \pm \Delta'_{\text{AOM}}, \quad (2)$$

where $\Delta'_{\text{AOM}} = \Delta_{\text{AOM}} - \Delta_{\text{FSR}}$ (see Figs. 2(b) and 2(c)).

From the new lock point, the dye laser can again be tuned by slowly adjusting the AOM frequency, but this time within one FSR adjacent to the original tuning range (see Fig. 2(d)). Throughout the following we will refer to the fast AOM frequency adjustments as ‘jumps’, and to the slow AOM-frequency tuning as ‘scanning’. In practice, the bandwidth of the dye laser servo loop allows scanning at rates up to 500 MHz/s, while frequency jumps are made at rates

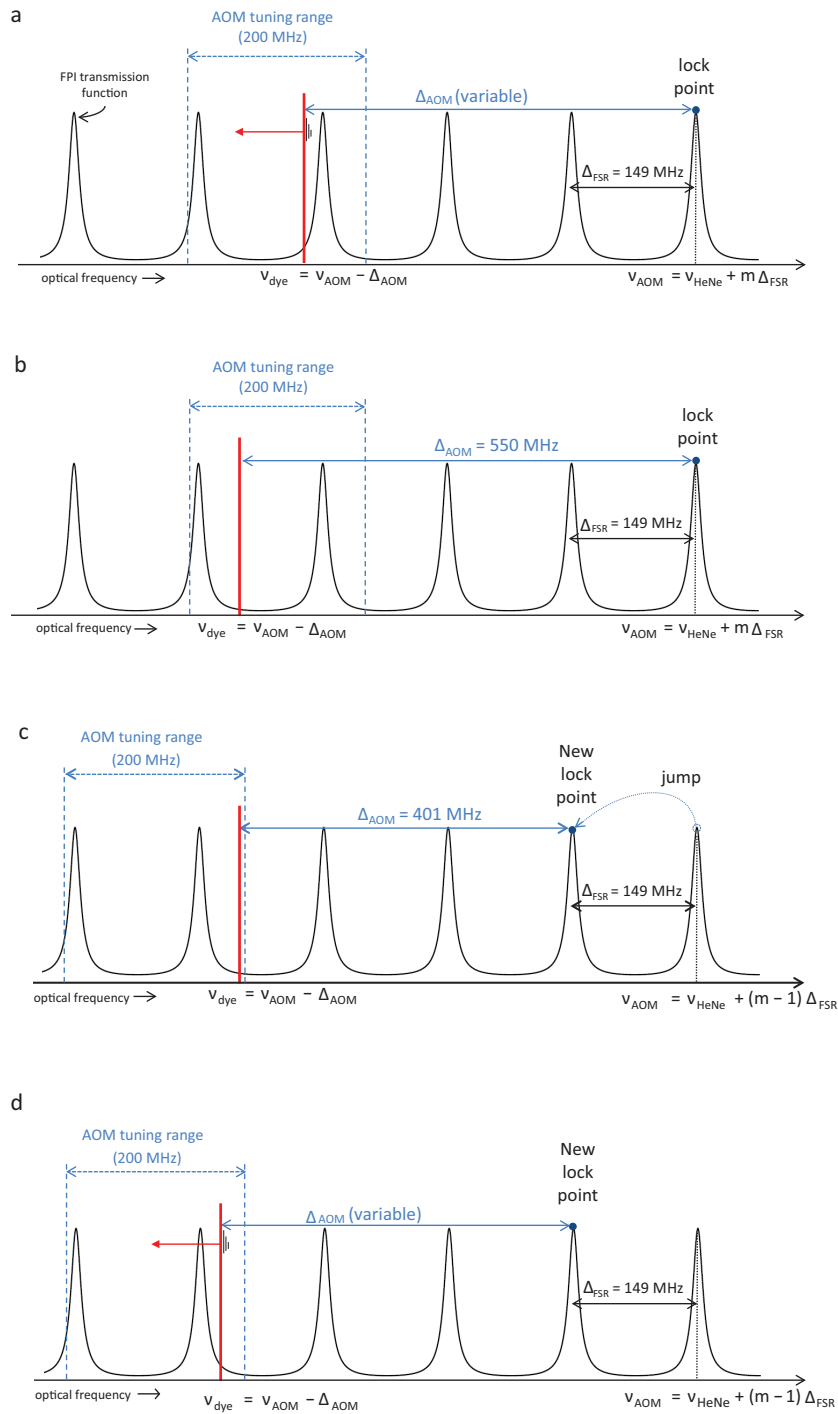


Fig. 2. Illustration of the 'AOM-jump method': (a) the dye laser is scanned in a controlled way by RF tuning of the AOM within the AOM tuning range; (b) near the edge of the AOM tuning range the scan is stopped; (c) subsequently the AOM frequency is rapidly adjusted so that Δ_{AOM} jumps by Δ_{FSR} without perturbing the frequency of the dye laser; (d) the dye laser is ready to be scanned by one FSR adjacent to the previous scan range.

in excess of 10 THz/s. In principle, the process of scanning and jumping can be repeated indefinitely, thus allowing large frequency ranges to be covered. Furthermore, this widely-tunable offset lock method works for frequency scans in either direction (*i.e.* toward higher or lower optical frequencies). An analogy can be drawn between this method and the dragging of a computer mouse over a mousepad: after dragging the mouse from the bottom to the top edge of the mousepad (scanning), the mouse can be lifted and placed back at the bottom edge (jump) to enable a next drag across the mousepad. In this way a mouse pointer on a computer screen can be dragged over arbitrary long distances while using a space no larger than the dimensions of the mousepad. In the present case of laser frequency tuning, the process can be repeated not only indefinitely but also reproducibly as long as the servo loop remains closed. In practice, the tuning range is limited by any process that will break the servo loop, such as mode-hops of the laser that is being tuned, or the servo loop output voltage hitting the rail voltage of the electronics. Also, the method will cease to work for wavelengths for which the FPI finesse is reduced (due to loss of mirror reflectivity) so that a reliable error signal for locking cannot be obtained. However, all the above limitations are technical and not inherent to the method itself.

The frequency shift applied to the AOM during a jump should be close to Δ_{FSR} , but does not necessarily have to equal this value: the servo loop will compensate for any small frequency mismatch within the linewidth of the FPI after the jump during the scan phase. As a result, a wide-range frequency scan through N successive jumps and scans will cover a frequency range of exactly $N\Delta_{\text{FSR}}$, apart from additional frequency adjustments made before the first jump and after the last jump of the scan.

Even if the exact values of ν_{HeNe} and m from (1) and (2) are unknown, absolute frequency measurements can be done if the dye laser is calibrated against a well-known optical frequency. In this way (and as shown in 3.2 below) optical spectroscopy can be accomplished within the 30 GHz mode-hop-free tuning range of the dye laser with an accuracy dependent on the accuracies of Δ_{FSR} , Δ_{AOM} , the frequency calibration, and the stability of ν_{HeNe} .

3. Results and discussion

3.1. Frequency calibration

With the wide-tunable offset lock presented here, we are able to tune the dye laser over a range of 30 GHz (the maximum scan range admitted by the dye laser control electronics) with a speed of ~ 500 MHz/s through simple RF tuning. During such wide-range scans, the frequency detuning from the initial frequency can be inferred by summing two parameters, namely the instantaneous VCO frequency, and the number of FSRs jumped over. This necessitates calibration of the voltage-frequency relationship of our VCO, as well as the FSR of the FPI. To calibrate the VCO, the VCO output is first mixed with the output of a stable RF signal generator of known frequency, after which the low-passed mixer output is fed into a frequency counter. The calibration accuracy is 10 kHz limited by long-term drifts of the VCO.

In order to make a jump of one FSR one has to know the approximate value of the FSR. In case the FSR of the FPI is unknown a coarse value can be easily obtained by making a series of jumps within a frequency range that encompasses the FSR. By monitoring the change in transmission at each jump using PD2 (Fig. 1), the line shape of the FPI transmission maximum can be traced out. In our case a series of 69 jumps (each starting from the same initial frequency which in this case corresponds to a transmission maximum of the FPI) in the range of -21 MHz to $+166$ MHz revealed the FPI transmission function from which a value of the FSR is extracted with better than one percent accuracy.

We also point out that instead of using a length-stabilized FPI, one might use a self-referenced optical frequency comb laser which is locked to some optical atomic or molecular reference frequency by stabilizing the repetition rate of the frequency comb [7]. In this case, the fixed

frequency comb spectrum can replace the FPI in our method. For example, the servo loop of our method may stabilize the beat-note frequency between the double-pass AOM output beam and the nearest mode of the frequency comb. Again, fast AOM jumps by exactly one repetition rate of frequency comb would not influence the servo loop that controls the CW laser frequency.

3.2. *Fast linear scanning and frequency reproducibility: demonstration through I₂ spectroscopy*

As a first demonstration, we employ our widely-tunable offset lock to record a 27-GHz-wide portion of the absorption spectrum of I₂. To this end, the dye laser output is directed to an existing setup for saturated absorption spectroscopy in an I₂ vapor cell [10]. As the I₂ spectrum has been well calibrated [11, 12], it can also serve to independently determine the FSR of the FPI, and to assess the overall performance of our method.

To demonstrate the wide tuning range and reproducibility offered by the widely-tunable offset lock, we acquire six copies of the 27-GHz-wide iodine absorption spectrum by alternately scanning the dye laser upward and downward across the spectrum. The servo loop remained closed throughout all scans, which were taken in the course of 1.5 hours. The absorption signal and the output voltage sent to the VCO are simultaneously recorded by two analog voltage input channels of the PC that also controls the experiment. To achieve a linear frequency scan over time, a nonlinear voltage ramp is applied to the VCO which precompensates the nonlinearity of the VCO. The horizontal axis is converted from voltage to frequency by counting the number of jumps (each of which corresponds to one FSR), and using the VCO calibration to find the frequency between the jumps (Sec. 3.1). Each spectrum in Fig. 3 is taken at two different scan rates: the two regions containing strong absorption features (separated by about 20 GHz) are taken at 25 MHz/s to achieve a good signal-to-noise ratio, whereas the intermediate 20 GHz span is covered at a higher rate of 300 MHz/s to speed up the data acquisition. Figure 3 only shows the parts of the spectra taken at 25 MHz/s. The I₂ spectra in Fig. 3 are ordered chronologically with the final spectrum on top.

We have compared the frequencies of the various absorption features in Fig. 3 with their known values from literature [11, 13] to infer an independent value for the FSR of our FPI. For example, the frequency difference between the features indicated by the thick dashed lines in Fig. 3 is 24908.7(1) MHz [13]. We find that this corresponds to 167.18(2) times the FSR, which yields $\Delta_{\text{FSR}} = 148.99(2)$ MHz.

In order to obtain absolute optical frequencies we calibrated the dye laser frequency with respect to the a₁ hyperfine component of the I₂ P60(7,3) transition ($\nu_{I_2} = 476.300358(3)$ THz [13]), indicated by the thick dashed line at 0 GHz in Fig. 3. Within the entire frequency tuning range of 30 GHz with respect to the optical frequency standard the absolute frequency accuracy is better than 6 MHz.

The spectra taken at 25 MHz/s in opposite scan directions reveal a frequency lag of 6(1) MHz of the dye laser frequency with respect to the frequency as determined from the VCO control voltage. The lag is clearly visible in Fig. 4, and stems from the limited response time of the electronics. A Laplace-transform analysis of the servo-loop electronics predicts a contribution to this lag of 0.1 MHz (which is determined by the loop gain and scan speed), while a similar analysis of the I₂ spectroscopy electronics reveals a 7 MHz lag caused by the low-pass-filter time constant chosen to record spectra with good signal-to-noise-ratio. The 7.1 MHz total lag is in agreement with the observed lag. Note that this frequency lag is not inherent to the method, apart from the small 0.1 MHz servo lag which may be reduced by an increased servo loop bandwidth or a reduced scan speed. The Laplace-transform analysis also points out that the servo lag ultimately limits the maximum scan speed to 0.5 GHz/s, which we verified experimentally. At this scan speed, the servo-loop frequency lag (6 MHz) approaches half the value of the FWHM

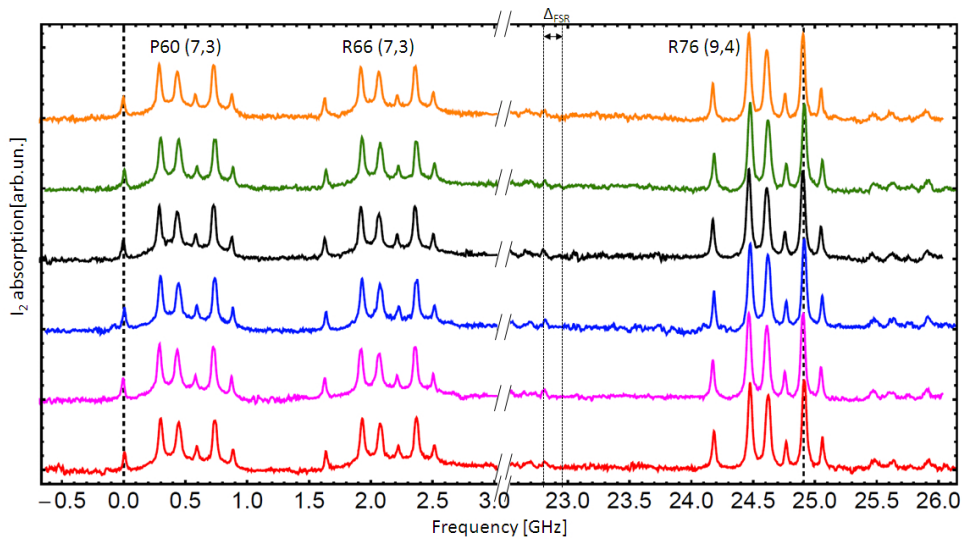


Fig. 3. Six traces of part of the I_2 spectrum recorded using the widely-tunable offset lock. The curves were alternately taken in upward and downward scan directions, starting from -0.65 GHz upward (bottom spectrum was taken first). The frequency difference between the absorption features indicated by the thick dashed lines is 24908.7 MHz. The left thick dashed line at zero frequency corresponds to $476.300358(3)$ THz.

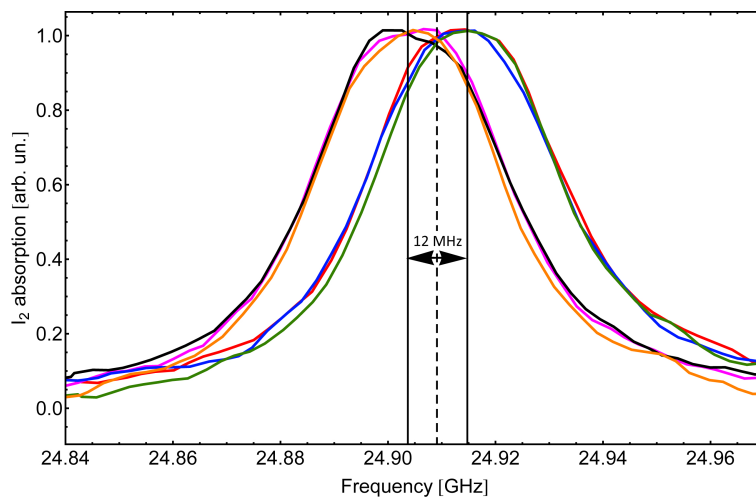


Fig. 4. Zoom-in of the spectra of Fig. 3 between 24.84 and 24.97 GHz. The scans taken in forward direction and in backward direction display a relative displacement of about 12 MHz, caused predominantly by the finite response time of the I_2 signal detection electronics.

width of the FPI line shape, *i.e.* the lock point is shifted to one of the extrema of the error signal which define the capture range of the servo loop.

Apart from the frequency lag, Fig. 4 confirms that our widely-tunable offset lock can reliably and reproducibly set the dye laser frequency with a precision of 1 MHz. In principle, this precision may be further improved by using a more stable optical reference frequency to stabilize the FPI, and by using an FPI with a larger finesse so that a tighter frequency lock of the dye laser is achieved. Laser frequency stabilization to FPIs at the 1 Hz level is nowadays routinely achieved, while optical frequency standards have achieved sub-Hz accuracy [14]. A tighter lock may also increase the maximum scan rate: given the 10–15 μ s response time of our VCO, we could in principle improve the response time of our servo loop by a factor of 1000 to a few 100 μ s, while still keeping the AOM jumps invisible to the servo loop. It therefore appears feasible to increase the maximum scan rate from 0.5 GHz/s to 0.5 THz/s.

The ability to offset-lock a laser at large, variable frequency offset is also of interest for coherent optical manipulation experiments which require high-intensity laser beams at large (10-200 GHz) detuning from resonance lines in atoms [15] and ions [16].

4. Conclusion

We have demonstrated a simple RF method to continuously scan the frequency of a narrow-band CW dye laser within its 30 GHz mode-hop-free tuning range, with a controlled offset from an optical reference frequency at 5 THz. The method employs an AOM placed inside the servo loop that locks the dye laser to a length-stabilized FPI, and allows automated RF scanning and relocking to adjacent FPI modes without breaking the servo loop. Frequency stability and reproducibility of better than 1 MHz within the entire 30-GHz tuning range and over time scales longer than one hour were demonstrated, and linear scanning at rates up to 500 MHz/s achieved. Moreover, calibration of the dye laser frequency using a well-known optical transition leads to an absolute optical frequency accuracy of better than 6 MHz. We expect that considerably higher accuracy and faster scan rates can be achieved using high-finesse FPIs and high-bandwidth control loops. We have addressed various technical aspects that determine the performance of our method. The stability and reproducibility of our widely tunable offset lock have been verified through spectroscopy of a known portion of the spectrum of I_2 . The method is generally applicable to other types of single-frequency CW lasers in other wavelength ranges, which makes it potentially useful for other areas of research, requiring stable yet widely-tunable laser sources, including atom interferometry [15], and quantum information processing using trapped ions [16].

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