

Absolute frequency measurement of an acetylene stabilized laser using a selected single mode from a femtosecond fiber laser comb

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Abstract: We performed an absolute frequency measurement of an acetylene stabilized laser utilizing a femtosecond injection locking technique that can select one component among the fiber laser comb modes. The injection locking scheme has all the fiber configurations. Femtosecond comb lines of 250 MHz spacing based on the fiber femtosecond laser were used for injection locking of a distributed feedback (DFB) laser operating at 1542 nm as a frequency reference. The comb injected DFB laser serves as a selection filter of optical comb modes and an amplifier for amplification of the selected mode. The DFB laser injection locked to the desired comb mode was used to evaluate the frequency stability and absolute frequency measurement of an acetylene stabilized laser. The frequency stability of the acetylene stabilized laser was measured to be 1.1×10^{-12} for a 1 s averaging time, improving to 6.9×10^{-14} after 512 s. The absolute frequency of the laser stabilized on the P(16) transition of $^{13}\text{C}_2\text{H}_2$ was measured to be 194 369 569 385.7 kHz.

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OCIS codes: (120.3930) Metrological instrumentation; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (140.3520) Lasers, injection-locked

References and links

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1. Introduction

The optical frequency comb generator (OFCG) is an attractive optical reference source for various applications such as optical frequency metrology and high-resolution spectroscopy [1-3]. In particular, the OFCG can be used as a reference source for absolute frequency measurement (AFM), providing a precise ruler in the frequency space [1-3]. Although each mode of the OFCG is coherent with one another and their frequencies are very stable, it is difficult to directly use a given mode of the OFCG as an independent light source, the main obstacles being the difficulty of mode selection and insufficient power per mode [3]. However, there are no suitable optical filters for only one selection among comb modes with very narrow spacing and at a mode power of several hundred nanowatts.

Recently, our group developed a method to independently select and amplify each comb mode by an injection locking technique [4]. This method could be applied to obtain a laser source selecting only one desired mode of the optical frequency comb and amplifying the power of the selected mode several thousand times. This source has been used in applications such as optical frequency synthesizers [5]. Furthermore, the multi-frequency coherent sources generated by the OFCG can be applied to coherent spectroscopy [6]. These may provide a useful technique in optical frequency standards based on multi-photon schemes [7,8]

However, because the OFCG has a low and irregular comb mode power, frequency counter error can arise due to beat detection with a low signal to noise (S/N) ratio in the case of direct AFM [9]. An independently coherent light source, however, can be employed to solve the problem of extremely low power of each comb mode, because an injection locked DFB laser has high power as well as characteristics of the OFCG. The beating signal between the stabilized laser and the selected mode of OFCG can be obtained at a high S/N ratio. Nevertheless, the selected mode of the OFCG has not yet been applied to measure the absolute frequency of a stabilized laser. In addition, this system is limited for practical applications, such as using an AFM as an independent optical source without additional equipment in the optical communication field [10,11].

In this paper, we select a single mode from a fiber femtosecond laser comb with a very narrow spacing of 250 MHz and demonstrate the absolute frequency measurement of an acetylene laser stabilized on the P(16) transition of $^{13}\text{C}_2\text{H}_2$ as the wavelength standard in the 1.5 μm region using an injection locked DFB laser at the desired comb mode of an OFCG based on a fiber femtosecond laser. To our knowledge, our experimental results are the first ever reported practical application for absolute frequency measurement of an infrared laser using a selected single mode from a femtosecond fiber laser comb. The measurement system consists of passive components based on fiber that is easy to handle, including the OFCG and the injection locking setup of DFB lasers.

To measure the absolute frequency of a laser, it is possible to directly measure the beat frequency between an injection locked DFB laser and an acetylene stabilized laser. In the present work, we measure the absolute frequency of an acetylene laser stabilized on the P(16) transition of $^{13}\text{C}_2\text{H}_2$ and compare the result with the value recommended by the Consultative Committee for Length (CCL), i.e., 194 369 569 384 kHz, with an uncertainty of 5 kHz (2.6×10^{-11}), for the P(16) transition of $^{13}\text{C}_2\text{H}_2$ [12].

2. Experimental setup

Figure 1 shows a schematic of the experimental setup for the absolute frequency measurement and stability evaluation of the acetylene stabilized laser using an injection locked DFB laser.

The OFCG (Menlo Systems, FC1500) based on a polarization-mode-locked femto-second fiber laser offers reference frequencies with comb modes of 250 MHz spacing for injection locking of a DFB laser. The repetition rate (250 MHz) and the carrier-envelope-offset (CEO) frequency (20 MHz) of the OFCG were stabilized by using an H-maser for the frequency reference. The CEO frequency was detected by the f-2f technique. The total output power and center wavelength of the OFCG are 200 mW and 1560 nm, respectively. The injected power of the OFCG was adjusted through a variable attenuator (VAT). An output coupler (OC, 50:50) was used to monitor the comb power entering the DFB laser by a power meter (Advantest Q8221). After passing through the output coupler, the optical comb enters the polarization controller (PC). The PC is not only necessary to adjust the polarization of the optical comb, but also to control the polarization in optical fibers, which are highly sensitive to polarization due to external disturbances such as temperature or vibration. An array waveguide grating (AWG: PPI Inc.) was used to filter the desired bandwidth of the optical comb. The wavelength of the AWG can be tuned 0.01 nm per 1 °C by an adjustable temperature controller in a range of 30 °C to 80 °C. The mode filtered combs were injected into the DFB laser through the circulator. In order to inject the comb modes into the DFB laser, a DFB laser module (FITEL) without an isolator was installed behind the PC. The center wavelength of the DFB laser is 1542.72 nm at an output power of 30 mW and can be tuned by adjustment of current and temperature. An acetylene stabilized laser (NEOARK) was used for two purposes, as a source to monitor the injection-locked status of the DFB laser, and as a test source for absolute frequency measurement and stability evaluation. The beat frequency between the acetylene stabilized laser and the injection locked DFB laser was detected by a photo detector (PD) and recorded by a frequency counter (Agilent 53132A Universal Counter) synchronized to a time base obtained from the H-maser with a relative stability of 2×10^{-13} at 1 s.

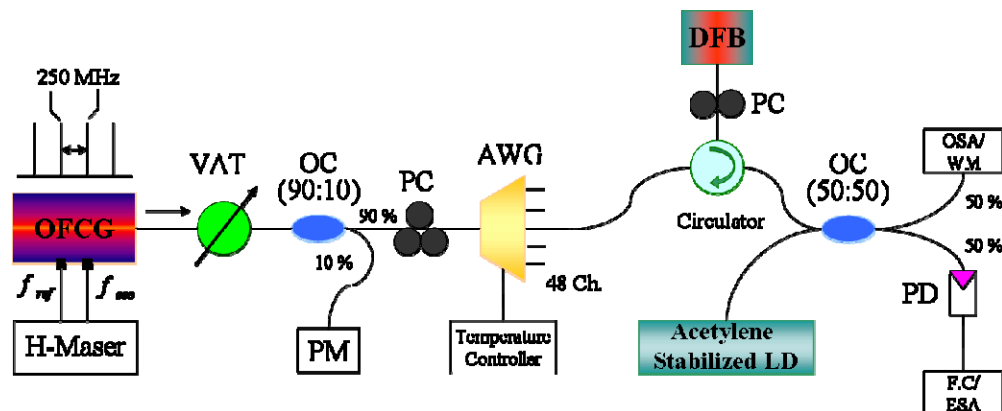


Fig. 1. Configuration of the experimental setup for injection locking of DFB lasers. The optical frequency comb generator (OFCG) was used for the injection seeding. VAT : variable attenuator, OC: output coupler, PM : power meter, PC : polarization controller, AWG, array waveguide grating, PD : photo detector, OSA : optical spectrum analyzer, WM : wavelength meter, FC: frequency counter, EAS : electrical spectrum analyzer

3. Experimental results and discussion

Figure 2 shows the output spectrum of the fiber femtosecond laser. The output of the fiber femtosecond laser was amplified and subsequently broadened in a highly nonlinear fiber to cover a frequency spectrum of one octave for determination of the CEO frequency by the f-2f technique (not shown in the figure). The inset of Fig. 2 shows the transmittance spectra of the AWG measured using a tunable laser. One channel among the AWG can determine the

allowable number of comb modes within limited linewidth. The AWG has a full width half maximum (FWHM) of 0.4 nm (~ 50 GHz) with 100 GHz channel spacing. In other words, the number of comb modes with 250 MHz spacing can be limited to approximately 200 within the FWHM of the AWG. After passing through the circulator, the injected comb power into the DFB laser cavity was about $380 \mu\text{W}$, and the power per comb mode was estimated to be approximately $1.9 \mu\text{W}$.

The output spectra of the DFB laser after [line (3)] and before [line (2)] comb injection locking are shown in Fig. 3. The filtered optical combs from the AWG [line (1)] are injected into the DFB laser without an isolator. After the injection of the comb, the S/N ratio of the DFB laser was improved by approximately 2.56 dB relative to that before injection locking. In other words, the S/N ratio of the injection comb was also improved by the amplification process of the DFB laser. The linewidth also was reduced (not shown in the figure) due to the optical spectrum analyzer's (OSA) limited resolution of about 1.25 GHz. In addition, the spectral width of the beat signal between two respectively injection-locked DFB lasers was less than 2 Hz with the limited resolution of the ESA. As mentioned above, even though each comb mode has a very low power of a few μW and narrow spacing, an individual comb mode can be used as an independent laser source through injection locking of the DFB laser, which serves as an amplifier and a mode selection filter.

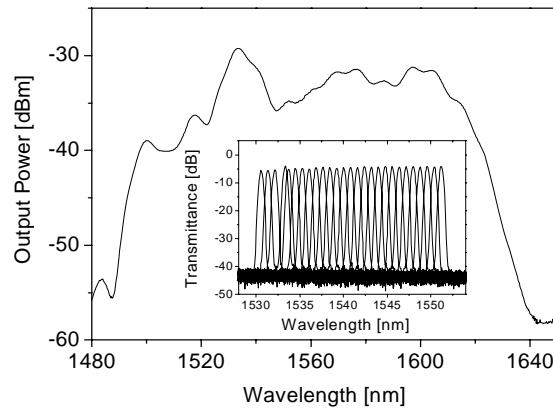


Fig. 2. The output spectrum of the amplified fiber laser oscillator for injection locking of the DFB laser. The insert is the transmittance spectra of the AWG. The channel spacing and FWHM are 100 GHz and 50 GHz, respectively.

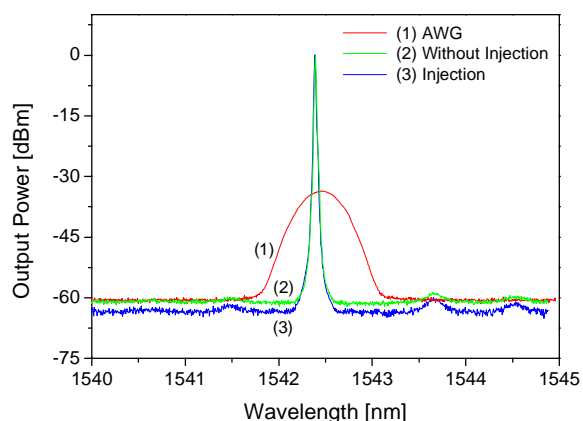


Fig. 3. Optical spectrum of DFB laser before and after injection locking centered at 1542.38 nm. Line (1) indicates the transmittance spectrum of the AWG. Lines (2) and (3) indicate that without injection locking and with injection locking of the DFB laser, respectively

To investigate the characteristics of the injection locked DFB laser, an acetylene stabilized laser was used as a probe beam. If one beat frequency between the two lasers is shown in the frequency domain, then only one mode among the combs has achieved injection locking into the DFB laser. Figure 4(a) shows the beat frequencies between the combs and the acetylene stabilized laser, measured by the ESA when injection locking was not achieved. The beat frequencies of 4.7 GHz and 4.75 GHz are the comb mode and the lasing signal of the DFB laser, respectively. The other comb modes of 250 MHz spacing centered on 4.7 GHz are also shown in Fig. 4(a). The beat frequencies of 50 MHz spacing are attributed to the harmonics and sub-harmonics between the combs (4.7 GHz) and the DFB laser (4.75 GHz). By finely adjusting the current to DFB laser, the lasing frequency can be exactly tuned at the desired comb mode. Figure 4(b) shows the beat frequency between the injection locked DFB laser and the acetylene stabilized laser when one among the comb modes achieved injection locking into the DFB laser. The DFB laser was injection locked to the comb mode of 4.7 GHz, shown in Fig. 4(a), and the optical spectrum is given by line (3) in Fig. 3.

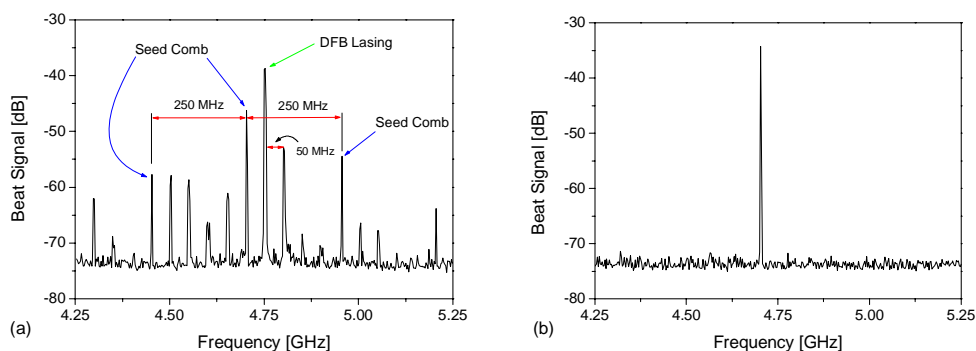


Fig. 4. (a). The RF spectrum between the comb and the DFB laser before injection locking. The comb spacing is 250 MHz, and the beatings of 50 MHz spacing are harmonics and sub-harmonics between the combs and DFB laser. (b). The beat frequency between the acetylene stabilized laser and the injection locked DFB laser

However, when the DFB laser was injection locked to the comb, the operation time was maintained for only a few minutes due to the highly sensitive optical fiber to polarization variation by the temperature change and mechanical vibration. In order to investigate the polarization dependence of the fiber in the proposed injection locking scheme, we located an in-line polarizer in front of the DFB laser before comb injection. Figure 5 shows the normalized polarization dependent power (PDP) in the fiber according to the elapsed time before and after optimization of the injection locking bandwidth. In Fig. 5, line (1) shows that the PDP is optimized by means of reduction of the pigtailed fiber length (patch cords for the connection between FC/APC and FC/PC) and application of a Styrofoam casing of passive components to prevent polarization variation due to external disturbances. With the optimized PDP, injection locking was maintained for more than 1 hour with a beat frequency as shown in Fig. 4(b). Line(2) shows the PDP of the comb itself before passing through the fibers. The PDP of the comb itself was small after propagating through the fiber. It appears that the comb power distribution reaches a steady state in the fiber as the dummy fiber [13]. When fiber length was not adjusted and the fiber components were not wrapped, the PDP changed by approximately 1.8 % during 1 hour, as indicated by line (3) of Fig. 5. Because the polarization variation of fibers and components induces change of the injection comb power, the polarization of pigtailed fibers must be maintained at a constant level.

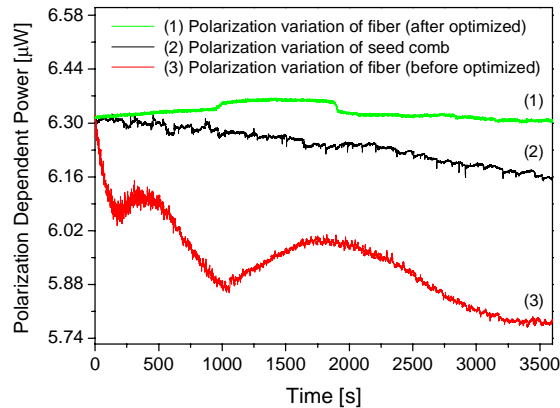


Fig. 5. The polarization dependent power in the fiber according to the elapsed time before and after the optimization of injection locking scheme. Lines (1) and (3) indicate the variation of the polarization dependent power before and after optimization of the fiber environment, respectively. Line (2) indicates the polarization dependence of the comb itself.

To evaluate the absolute frequency and the stability of the acetylene stabilized laser, we measured the beat frequency using a frequency counter, as shown in Fig. 4(b). The absolute frequency of the acetylene stabilized laser can also be estimated by the following equation: $f_{laser} = n f_{rep} \pm f_{ceo} \pm f_{beat}$. Figure 6 shows the Allan deviation of the measured frequency as a function of the averaging time. This was determined from the data with a gate time of 1 s in a juxtaposed manner. The right-hand inset in Fig. 6 shows the heterodyne beat between the acetylene stabilized laser and the comb injection locked DFB laser recorded by a frequency counter at 1 s gate time. Because the frequency counter has a limited bandwidth of 3 GHz, the center frequency of the beat signal was measured as 1 450 614 339.92 Hz by fine-tuning via the current of the DFB laser to select an appropriate comb mode.

The frequency stability of the acetylene stabilized laser was measured to be 1.1×10^{-12} for a 1 s of averaging time, improving to 6.9×10^{-14} after 512 s.

The absolute frequency of the laser stabilized on the P(16) transition of $^{13}\text{C}_2\text{H}_2$ was determined to be 194 369 569 385.7 kHz by the aforementioned equation. This is in good agreement with the updated value adopted at the 12th meeting of the CCL in 2005, i.e., 194 369 569 384 kHz, with an uncertainty of 5 kHz. Additionally, the left-hand inset in Fig. 6 shows the tracking capability of two DFB lasers simultaneously injection-locked to two different comb modes with 500 MHz spacing. The tracking capability is expressed in terms of the Allan deviation calculated by using the frequency counter data of the difference frequency (500 MHz) of the two injection-locked DFB lasers. This is obtained from separate data runs with the actual counter gate times (τ). The tracking capability for a sampling time of 1 s is 1.7×10^{-16} and has a $1/\tau$ dependence, indicating that the two DFB lasers are phase-locked.

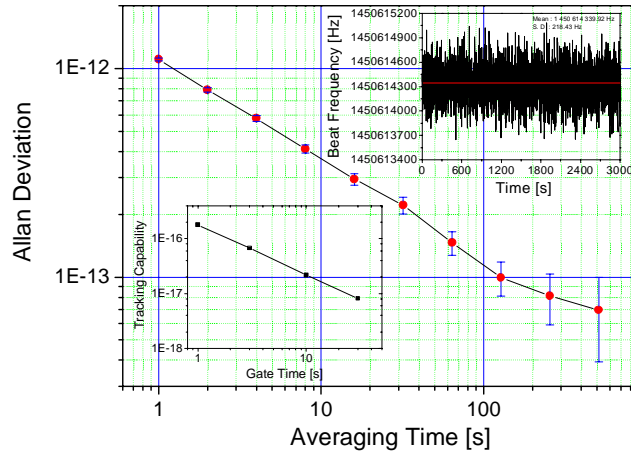


Fig. 6. The Allan deviation of the measured beat frequency between the acetylene stabilized laser and the comb injection locked DFB laser. The right-hand inset shows the beat frequency between this two lasers measured by a frequency counter. The left-hand inset shows the tracking capability of two independently injection-locked DFB lasers

4. Conclusion

We have demonstrated the absolute frequency measurement and the stability evaluation of an acetylene stabilized laser using a selected mode from an optical frequency comb generator (OFCG) with high stability. The injection locking schemes of a DFB laser consist of components based on fiber that is compact and easily aligned.

Because the DFB laser injected by the optical frequency comb has the stability of a master OFCG, it could evaluate the frequency stability of the acetylene stabilized laser. The measured absolute frequency and stability of the acetylene stabilized laser were 194 369 569 385.7 and 1.1×10^{-12} for a 1 s averaging time, respectively. These results agree well with recommended frequency value adopted by the CIPM and CCL. The injection locked DFB laser is expected to be adopted as a light source that can be used for the absolute frequency reference (AFR) of ITU-T grids and high-resolution coherent spectroscopy in the optical communications field.