APPLICATION NOTE

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Advanced Programmable Wavelength Markers For Swept Laser Based Test-Measurement Applications

Technology and Applications Center
Newport Corporation

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External (or extended) cavity diode lasers (ECDL) have been widely used in many metrology and test-measurement applications including telecom components characterization, fiber sensing, phase-shift interferometry, lidar, and bio-medical sensing and imaging, etc. Among the commercially available tunable lasers in the market today for industry applications, New Focus TLM-8700 tunable laser module [1] (Photonics Circle of Excellence award in 2004), which is engined by voice-coil based tuning mechanism, offers the fastest mode-hop-free tuning speed (up to 2,000 nm/sec in standard version, and up to 20,000 nm/s for certain OEM applications) in a wide wavelength tuning range (e.g., 110 nm in 1520-1630 nm)

For widely tunable laser, tuning speed and linearity are the terms or specifications quite often being used for characterizing the tuning performance. Tuning linearity is usually defined as the tuning speed deviation from a preset constant, while the wavelength tuning speed is defined by change rate of wavelength over time (dtdV/λλ=)(refer to Appendix).

In most of the applications where users are interested in tuning linearity, the traditional way to use widely tunable laser for measurement is to take data in an equal time spacing fashion while the laser wavelength sweeps. Any measured physical parameter, e.g., transmission of the device or system, would be characterized as a function of the wavelength. The conversion between the time and the wavelength is performed by assuming a constant tuning speed so that the sampled data points are labeled or assigned to wavelengths according totVtstartlabelλλλ+=)(. In any actual ECDL system like TLM-8700, possible deviations from a true constant tuning velocity due to system error and technical noises result in a non-perfect linear relationship between output wavelength and tuning time, the actual wavelength at measurement t will differ from labeled wavelength. The wavelength tuning linearity of TLM-8700 is achieved around 3-10% by the closed loop control on tuning speed. Figure 1 shows the tuning speed of TLM-8700, keeping flat in two orders of magnitude range.

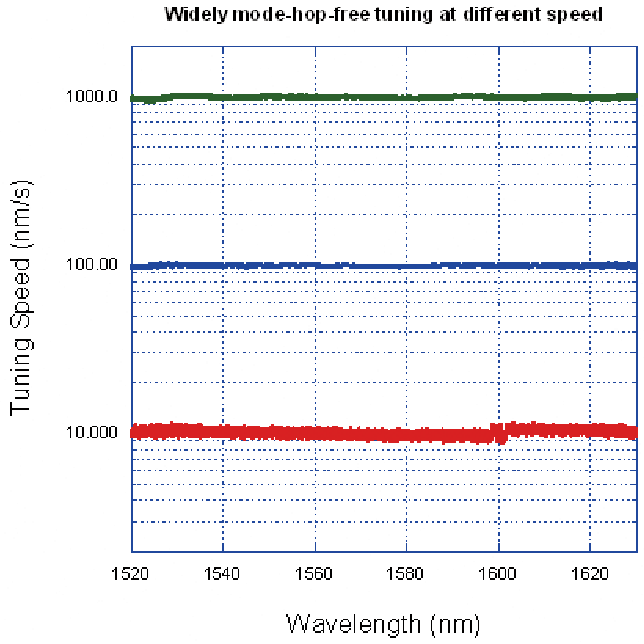

Figure 1. TLM-8700 *closed-loop control sweeping at different speed achieves* 3-10% *speed flatness in* 110 *nm tuning range across* 2 *orders of magnitude change in speed.*

From the system performance design point of view, there are two types of typical imperfection in actual tuning speed: the systematic calibration offset, and the technical noise caused local speed variations from the mean speed. Therefore, the total wavelength deviation from the true value contains two major components. One is the global absolute speed offset due to system calibration limit. The other one is the residual speed fluctuations associated with all other technical noises in the system including control loop imperfection. As analyzed in Appendix, both of them can cause significant wavelength deviations between the labeled wavelength and the true wavelength. Figure 2 shows an example of the swept wavelength as a function of time.

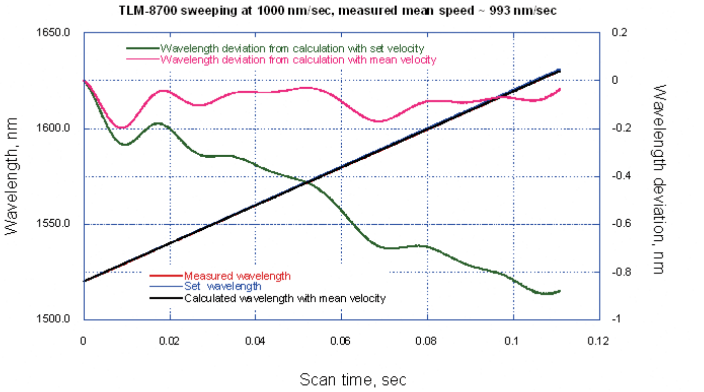

Figure 2. TLM-8700 *laser tuning wavelength and wavelength deviation as sweeping at a set speed of* 1000 *nm/s. The three straight lines (very close to each other) are the measured wavelength, calculated momentary wavelength at the set speed, and the calculated momentary wavelength at mean speed, respectively. The measured wavelength was the wavelength measured by calibrated optical etalon during scan and is considered as true wavelength for the sake of comparison. The mean speed is measured by the time spent for sweeping over the entire wavelength range. The red curve show the momentary wavelength deviation from the true wavelength by comparing to the set speed, and the green curve is the momentary wavelength deviation from true wavelength by comparing to the mean speed. In traditional applications, the measurement restults are usually labeled with either the set wavelength or the calculated wavelength with the mean speed after further calibration.*

To improve the accuracy in labeled wavelengths, one way that has been used in practice for data processing is to add a parallel measurement for tuning speed or swept wavelength and perform a post- scan calibration by employing data taken from additional wavelength references such as absorption lines from gas cell [2] or optical etalon fringes as wavelength markers. This additional complexity and cost as well as the time consumed for the process make the solution less attractive. On the other hand, advanced electronic devices for embedded system and data acquisition tool make it possible that the data is not necessarily taken with uniformly time spacing. Sampling measurement data points timed with their corresponding internal wavelength information during scan can make full use of the laser system calibration accuracy and therefore can significantly improve the wavelength accuracy for each data point instead of relying on time stamps assuming constant tuning speed. To this end, an advanced programmable trigger scheme has been introduced in TLM-8700 [3], which provides output trigger-signals to serve for data acquisition synchronization and wavelength markers. Figure 3 sketches the diagram of the output trigger- signals for wavelength markers and scan configuration information. In TLM-8700 laser system, the tuning position sensor signal is calibrated by the precision wavemeter during laser build, and a look-up table between the tuning position and the wavelength is stored in the system. As the laser is in tuning, a train of TTL pulses as narrow as 0.1-1 μsec is generated when the tuning arm passes each pre-programmed particular position or wavelength based on the calibration table, the number of the pulses can be programmed such that the consecutive pulses serve as even spaced markers in wavelength space. For example, in a 100 nm tuning range, 1001 wavelength markers, i.e., 0.1 nm spaced from start to stop wavelength, can be output while the laser is scanning. The wavelength accuracy of the pulse is primarily determined by the wavelength calibration and the pulse width. The short term accuracy, e.g., the time over individual scan, can be as good as a few pm, while in the long term, can be within 30 pm including all environmental change and components long term relaxation drift, etc. This long term wavelength drift can be further improved through periodic recalibration of laser.

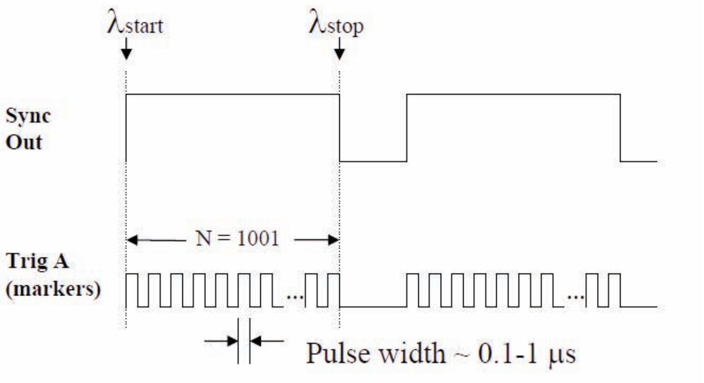

Figure 3. Diagram of the TLM-8700 *output trigger. Sync Out is the output signal which stays at one level with edges aligned with the start and stop wavelengths respectively. Trigger* A *signal is a train of* TTL *pulses, with programmable wavelength spacing; the first and the last pulses are aligned with Syn Out two edges.*

To evaluate the effectiveness of the wavelength markers for wavelength labeling in measurement, we use an NIST traceable HCN gas cell as sample, and the absorption spectrum was obtained by simple transmission detection as shown in Figure 4. Both transmission of the cell and the wavelength markers are acquired in parallel through a NI-5102 DAQ board with a Labview program, the wavelength axis is linearized by using fiducial of the wavelength markers output from the laser. Since the absorption peaks can be traced by the NIST data [4], by comparing the peak wavelengths, the wavelength accuracy at each peak has been confirmed to be within the laser wavelength calibration accuracy. Referring to Figure 2, the wavelength deviation would be as large as a few hundred pm using traditional method for wavelength labeling. The wavelength accuracy improvement with wavelength markers can be understood due to the fact that the accumulated wavelength error gets reset at each wavelength marker, therefore, up to two orders of magnitude improvement in wavelength accuracy has been achieved for the full range of TLM-8700 tuning range.

The wavelength marker repeatability has been evaluated by using the wavelength repeatability at each individual absorption peak in the transmission spectrum. A zoomed-in peak of the HCN P-branch (#4) is shown in Figure 4(b). The wavelength measured by using the wavelength marker reaches the accuracy limited by the calibration accuracy and the repeatability is 0.43 pm. In TLM-8700, both wavelength accuracy and repeatability are affected by the trigger pulse jitter and have been observed to be dependent on tuning speed. In the case of 1 μs trigger pulse width the wavelength repeatability has been achieved with the standard deviation to be < 0.2 pm at tuning speed of 100 nm/s, and < 0.8 pm at speed of 2000 nm/s.

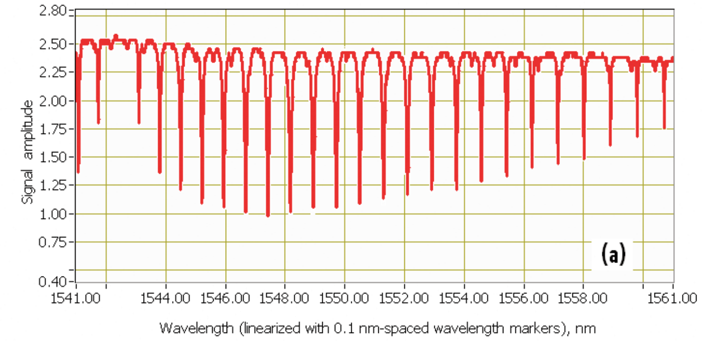

Figure 4 (a). A transmission signal through a 100 *torr* Hydrogen Cyanide *cell* (SRM2519) *as* TLM-8700 *sweeping at* 1000 *nm/s across the absorption peaks. The graph shows only part of the entire* R *and* P *branches due to data acquisition setup limit. The transmission signal and the wavelength markers are acquired in parallel. The wavelength is labeled with value linearized using* 0.1 *nm spaced wavelength markers. Although it is difficult to read the precise wavelength of each absorption peaks from the graph, a separate data analysis is performed and the difference between peak locations are compared with the* NIST *data. The absolute accuracy is achieved within the laser absolute wavelength accuracy (<*10 *pm in this case).*

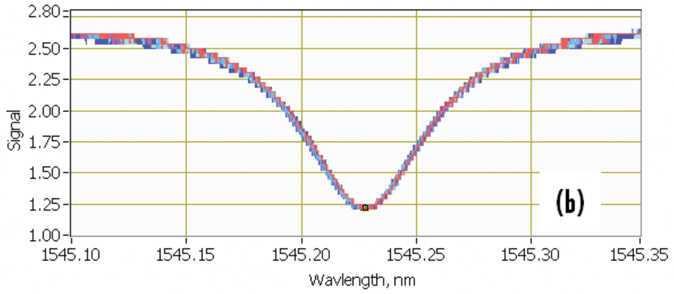

Figure 4 (b). A zoomed-in P-*branch* (#4) *absorption line with* 10 *repeatedly measured traces to show the highly repeatable peak location. The repeatability of the wavelength markers is demonstrated by using the markers for labeling the individual absorption peak. With the wavelength values linearized from the wavelength markers, The peak position is statistically analyzed from data acquired in multiple scans. The mean value of the peak position is obtained to be* 1545.228 *nm (compared to* 1545.230 *nm from* SRM 2519 P-*branch* (#4)P(4)) *and the standard deviation is achieved to be* 0.43 *pm with* 100 *scans at tuning speed of* 1000 *nm/s.*

It should be noted that the data processing in the example here is not the only way for using the wavelength markers. The pulse train of TTL outputs train can be also directly used for triggering the data acquisition.

In addition, the current hardware design in TLM-8700 has a limited memory size for the total number of markers. The wavelength repeatability can be further improved for application with narrower scan range. The width of the trigger pulse generated for the markers also contribute to the uncertainty or statistic error in wavelength accuracy of the markers especially in high speed applications since the ratio of the pulse width to the jitter would show as the marker position accuracy. Nevertheless, the current design of the TLM-8700 wavelength marker has achieved sub-pm repeatability and has provided a low-cost high-performance solution to a variety of precision test-measurement applications.

Recently, there are increased demands in evenly spaced sample in frequency domain for applications in swept laser based frequency domain optical coherence tomography (OCT). The advanced programmable trigger of TLM-8700 can accommodate this purpose conveniently by providing evenly-spaced frequency markers to facilitate the signal spectrum analysis with FFT [5].

In summary, the advanced programmable trigger in TLM-8700 provides flexible and precision wavelength markers for data acquisition and processing to the accuracy limited by the system calibration and system stability. The equivalent wavelength accuracy has been demonstrated to be improved by two orders of magnitude especially in wide and fast tuning applications. The absolute tuning linearity requirement is no longer a show-stopper for high speed and precision measurement applications.

Appendix

Parameters used in tuning linearity evaluation

The tuning linearity of continuously tunable or swept lasers is a parameter that specifies the error in the tuning speed. It can be defined as a function of tuning-speed deviation [in nm/s], and the wavelength deviation [in pm] can be related to the tuning speed variation at measurement time.

The momentary tuning speed deviation from the target tuning speed () can be expressed as: . The momentary tuning speed, Vn , is given by:setVsetnVVV−=Δ11−−−−=nnnnnttVλλ, where λn - λn-1 represents the local wavelength interval, and tn - tn-1 is the time interval between these two measured points. Tuning linearity is usually expressed by a relative percentage of the momentary tuning speed deviating from the set constant velocity as: %100%100×Δ=×−setsetsetnVVVVV. The relative momentary tuning speed deviation can be practically evaluated by using Vmean instead of , where the mean or average tuning speed for given wavelength range (from setVstartλto stopλ), Vmean, is given by:startstopstartstopmeanttV−−=λλ .

As shown in graph (Fig. 1), there are two main sources contribute to the total deviation from target, the systematic error due to limited uncertainty of calibration, and the residual fluctuations in speed in closed loop operation. The relative tuning linearity excludes the system error and therefore emphasize on technical noises in the speed control loop.

The momentary wavelength can be determined by integrating the tuning speed as follows:

dttVttactualstartactual∫+=0)()(λλ, where)()(tVVtVsetactualΔ+=, and is the preset target constant tuning velocity. In traditional measurement data processing, the measurement is performed with equal-time-distance sampling. The measurement results are labeled with wavelengths assuming the target speed, i.e., . setVtVdtVtsetstarttstartlabel+=+=∫λλλλ0)(

The momentary wavelength deviation from the expected momentary wavelength at time t is therefore given by:. dttVtttlabelactual∫Δ=−=Δ0)()()(λλλ

Since the contribution from different sources can be decomposed to a systematic offset (a constant) and a residual fluctuations from mean value offsetV))((meannVtV−, i.e., , so we have . offsetmeannVVtVtV+−=Δ))(()(tVdtVtVttoffsetmeann∫+−=Δ0))(()(λ

It should be noted that, in general, is presumably minimized through the system calibration (to zero ideally), however, any residual offset, e.g., a small relative speed offset will impose a relative large wavelength deviation especially for wide range of tuning; e.g., a Δλ=100 nm tuning with offsetVmeanoffsetVV%1= results in an 1 nm (=meanoffsetoffsetVVtVλΔ=) wavelength deviation at the end of the tuning. Although the detail analysis of the origin of is beyond the scope of this article, it should be mentioned that it is mainly limited by the speed of electronics for tuning speed control, and can be further calibrated by more sophisticated firmware. offsetV

The residual speed fluctuation from mean value has more effect on local wavelength deviation, characterized by a fluctuation characteristic time scale τ which is typically ~ 10-2-10-4 second in TLM-8700 system. Such a local wavelength deviation can be estimated by τpeakVΔ where is the peak momentary speed deviation; e.g., for τ~1 msec, and , results in a wavelength deviation of 0.1 nm at the tuning speed of 2000 nm/sec. peakVΔsetpeakVV%5=Δ

References

[1] www.newport.com, New Focus TLM-8700 tunable laser module.

[2] www.newport.com, New Focus TLB-6600 Venturi™ swept-wavelength tunable laser with Precision Wavelength Reference option.

[3] US patent application #US20060274798.

[4] Hydrogen Cyanide H14C14N Absorption Reference for 1530 nm to 1560 nm Wavelength Calibration - SRM 2519; S.L. Gilbert, W.C. Swann, and C.-M. Wang, NIST SP 260-137, NIST Standard Reference Material 2519, Nov, 1998

[5] High aAxial resolution swept source for optical coherence tomography; Cordes, A. H. Xavier, G.B.; Vilela de Faria, G.; von der Weid, J.P.; Elect. Lett. Vol. 46, No 1, p27-29 (2010)

Newport Corporation

Worldwide Headquarters
1791 Deere Avenue
Irvine, CA 92606

(In U.S.): 800-222-6440
Tel: 949-863-3144
Fax: 949-253-1680

Email: sales@newport.com

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