Understanding MEMS-VCSEL Bandwidth Definitions

THORLABS APPLICATION NOTE

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OPTICAL BANDWIDTH

MEMS-VCSEL swept laser sources emit a continuous optical spectrum by rapid modulation of the laser's cavity length using a tunable end mirror. Hence, different wavelengths are not emitted simultaneously, but sequentially, according to the position of the MEMS mirror. A sweep denotes the movement of the mirror from one end of its travel range to the other. Hence, the terms "Wavelength Sweep Range" and "Optical Bandwidth" denote the optical spectrum emitted by the laser during one full sweep. This range of wavelengths is represented by $\Delta\lambda_{sweep}$. The optical bandwidth is defined as the spectral width at -10 dB attenuation, or the wavelength difference between spectral positions where the intensity is 10% of the maximum intensity. An example swept laser spectrum measured with Thorlabs' OSA202C Optical Spectrum Analyzer is shown in Figure 1.

All MEMS-VCSEL swept laser sources are equipped with a fiber-optic Mach-Zehnder Interferometer (MZI) with balanced detection of both interferometer outputs. One arm of the MZI has a fixed optical path delay with respect to the other arm (Δl_{MZI}). Because the wavelength changes over time and Δl_{MZI} does not, the MZI output forms a sinusoidal voltage over time:

$$V_{MZI}(t) \propto cos[k(t)\cdot\Delta l_{MZI}] \qquad (1)$$

The wavelength here is represented in terms of the wavenumber, k. The sinusoid is then digitized to give a square-wave TTL signal called the k-clock, shown in Figure 2.

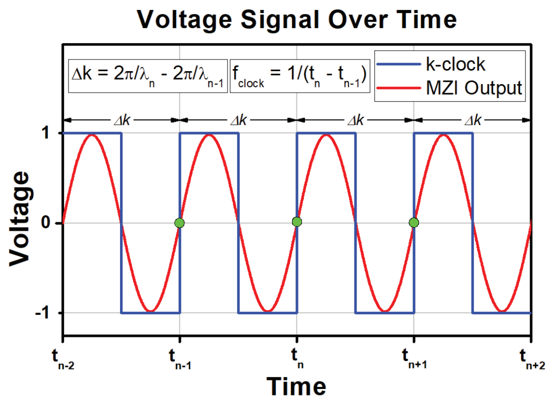
Figure 1 (Below): Measurement of a Wavelength Sweep Range. Optical bandwidth is typically >100 nm for Thorlabs' SL10 and SL13 series laser sources.

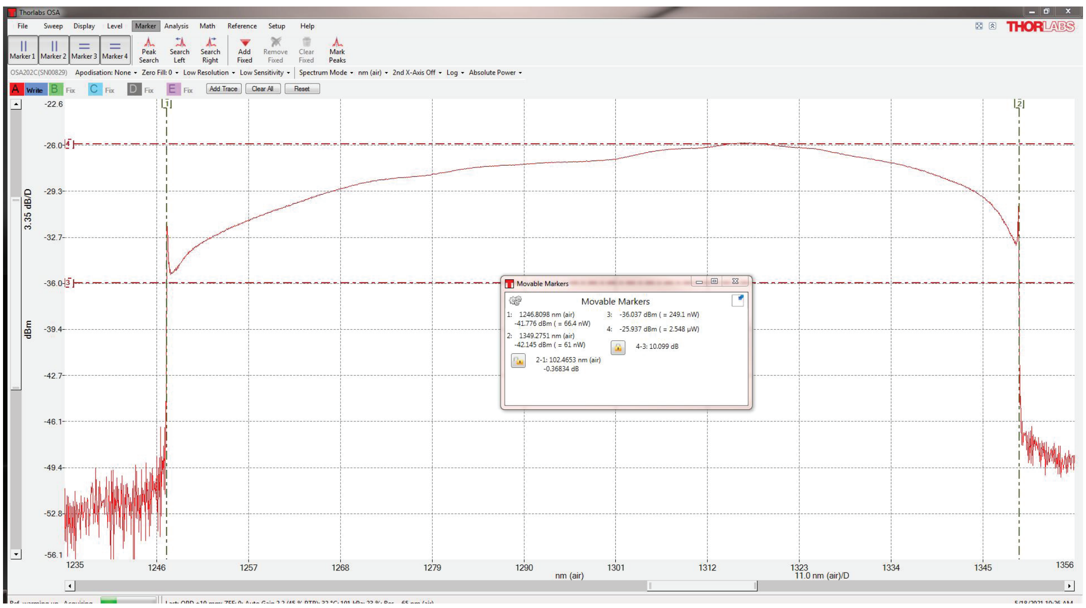
Figure 2 (Right): Signal Output of a Laser's k-Clock. The green dots mark the k-clock trigger points.

The benefit of this approach is that neighboring zero-crossings of the voltage signal are precisely shifted by a constant $\Delta k = 2\pi\cdot\Delta\lambda/\lambda^2$. The zero-crossings are referred to as "k-clock-points" or "k-clock-triggers" and allow exact mapping of time and wavenumber changes. Hence, the k-clock gives a relative measure of the emitted wavenumber (or wavelength) during a sweep.

The instantaneous k-clock frequency, f_{clock}, typically reaches values up to 900 MHz depending on the laser's sweep rate and MZI delay. Apart from that, lab measurements reveal that the k-clock signal can exhibit strong noise or spikes when the MEMS mirror approaches its end positions, as shown in Figure 3. These spikes are not visible in the spectral domain, and so they do not affect the optical bandwidth. However, they represent frequency values that easily exceed the detection bandwidth of even high-end data acquisition cards, which means the full optical bandwidth of one sweep cannot be reliably mapped to time using the k-clock. For this reason, the "k-clock sampled bandwidth" or "sampled bandwidth" $\Delta\lambda_{sam}$ denotes the spectral range that can be reliably sampled with the k-clock. It is typically 5 nm smaller than the optical bandwidth:

$$\lambda_{sam} \approx \lambda_{sweep} - 5\,nm \qquad (2)$$





RESOLUTION IN OCT AND NUMBER OF K-CLOCK POINTS

In OCT, usage of the k-clock is mandatory for mapping acquired data to the corresponding wavenumber. Thus, the achievable axial pixel spacing of OCT in air, δz, is based on the k-clock sampled bandwidth. With the center wavelength λ_c, and assuming the penetration medium is air ($n \approx 1$), pixel spacing can be estimated by the following approximation:

$$\delta z = \frac{2 \cdot \ln(2)}{n \cdot \pi} \cdot \frac{\lambda_c^2}{\Delta\lambda_{sam}} \approx 0.5 \cdot \frac{\lambda_c^2}{\Delta\lambda_{sam}} \qquad (3)$$

To evaluate resolution capability of a swept laser source in terms of OCT, it is not sufficient to consider the optical bandwidth nor the sampled bandwidth independently, as slight variations in either value will have a strong influence on the resolution.

Thorlabs' MEMS-VCSEL lasers are specified with the number of k-clock points N that can be reliably sampled during one sweep. This number accounts for the optical influences on pixel spacing and is a direct measure of performance in terms of the OCT pixel spacing, δz.

$$\delta z \approx \frac{\Delta l_{MZI}}{2N} \qquad (4)$$

$$N \approx \frac{\Delta\lambda_{sam}}{\lambda_c^2} \cdot \Delta l_{MZI} \qquad (5)$$

The number of k-clock points measured with an oscilloscope does not always match the capabilities of some state-of-the-art data acquisition cards, which may require a multiple of 16, 32, 64 or 128 as k-clock points for their processing. The latter is checked with a commercially available card and the usable points are specified as "k-Clock: Minimum Points" (N_{min}). They are noted on the customer data sheet for each product together with the employed card, ensuring that customers can make use of the specified minimum number of points. Please note that the selection and implementation of any data acquisition card is the responsibility of the customer.

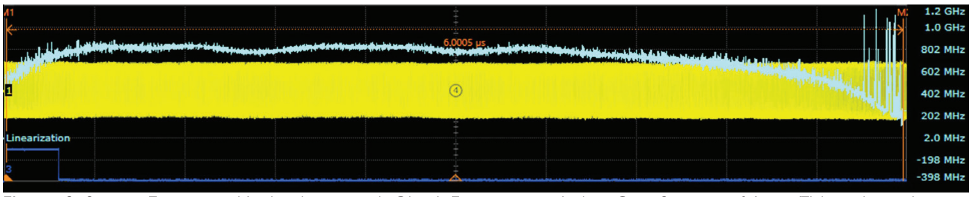


Figure 3: Scope Trace and Instantaneous k-Clock Frequency during One Sweep of 6 µs. (This system does not pass QC due to the spikes at the end of the sweep range.)

IMAGING DEPTH IN OCT

OCT requires interference in order to image a sample, and thus imaging depth depends on the coherence length of the light source. One advantage of MEMS-VCSEL swept sources is that instantaneous linewidth is very small, resulting in coherence lengths on the order of 1 or more meters and, theoretically, imaging is possible up to that limit.

In OCT, imaging depth and axial resolution are inversely proportional. Therefore, from equation (4), imaging depth increases proportionally with the number of k-clock points. By sweeping through k-clock frequency, the k-clock frequencies appear as time frequencies. The question of imaging depth in swept-source OCT then translates to a question of sample rate.

When sampling of the OCT signal is triggered by the k-clock, the k-clock frequency is equal to the sampling frequency. In equation (1), the frequency of the sinusoid over all values of k is Δl_{MZI}. From the Nyquist criterion, it follows that the sampled frequency can be a maximum of $\Delta l_{MZI}/2$. Keeping in mind that any distance within the sample arm of an interferometer needs to be traversed twice by the light (since the light makes a round trip), the actual limit of the imaging depth Δz_{max} must be smaller by an additional factor of 2:

$$\Delta z_{max} \approx \frac{\Delta l_{MZI}}{(2 \cdot 2)} \approx \frac{1}{4} \cdot f_{clock} \cdot \frac{\lambda_c^2}{\Delta\lambda_{sam}} \cdot \frac{D_{BOA}}{f_{MEMS}} \qquad (6)$$

In equation (6), f_{MEMS} is the sweep rate of the laser (typically 50 to 400 kHz), and D_{BOA} is the duty cycle of the laser (typically 30 to 70%).

The real imaging depth achieved by a system also depends on other application parameters such as sample absorption and scattering characteristics or the imaging lens used and its Rayleigh length.

Product	SL101060		SL131090	
Center Wavelength, $\boldsymbol{\lambda_c}$	1045 nm	1070 nm	1285 nm	1315 nm
Sampled Bandwidth, $\boldsymbol{\Delta\lambda_{sam}}$	94 nm	97 nm	94 nm	97 nm
MZI Delay, $\boldsymbol{\Delta l_{MZI}}$	48 mm	48 mm	44 mm	44 mm
Axial Pixel Spacing in OCT, $\boldsymbol{\delta z}$	5.8 µm	5.9 µm	8.8 µm	8.9 µm
No. of k-Clock Points, $\boldsymbol{N}$	4132	4067	2733	2693

Table 1: Pixel Spacing in OCT. The number of k-clock points correlates directly with resolution.

Curious for more? Please contact oct@thorlabs.com for more information on the specifications and possible customizations. We are eager to discuss your application and learn about your requirements!