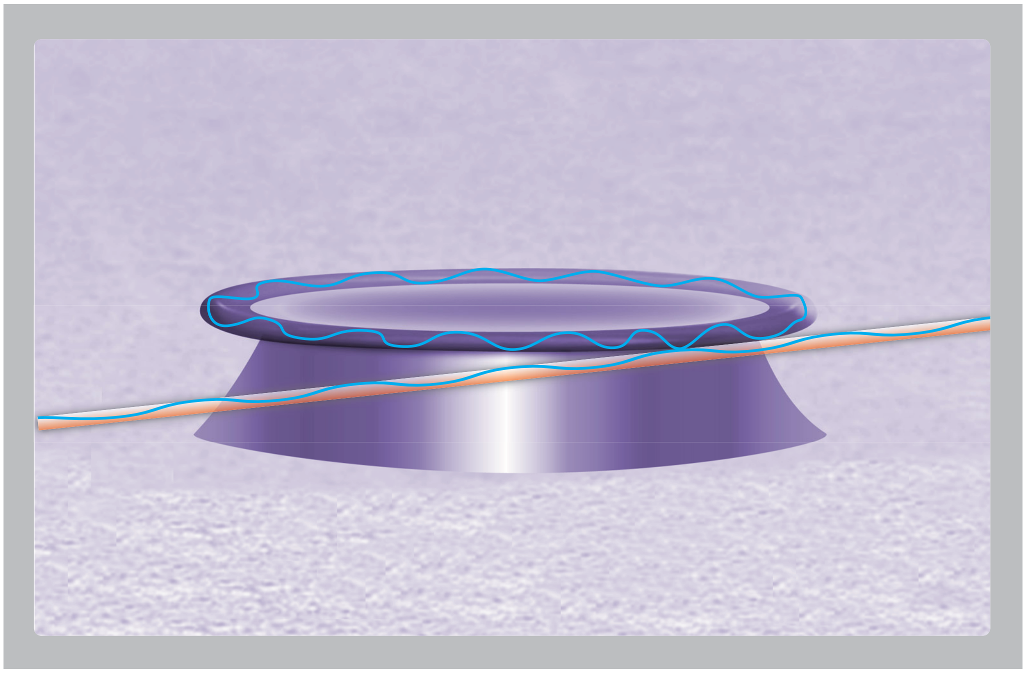
New Focus™
A Newport Company

Tunable Diode Lasers



Simply Better™ Photonics

New Focus: Simply Better™ Photonics

Founded in 1990 with the mission of providing Simply Better™ Photonics Tools, New Focus has built a portfolio of high-performance products that includes tunable lasers, opto-electronics, high-resolution actuators, stable optomechanics, vacuum and ultraclean solutions, and OEM engineered solutions. Our products are used in demanding applications around the world in semiconductor equipment, bio-medical research, industry, test and measurement and advanced research.

As part of Newport we continue our focus on making great tools for scientists and researchers.We are taking all the engineering we have learnt in the industrial world and have remade all our legacy tunable lasers and high speed electronics products. You will see the results of that in the new products we have launched recently.

We believe tools that you use in the lab should be just that, simple and reliable tools, not an experiment in a box.

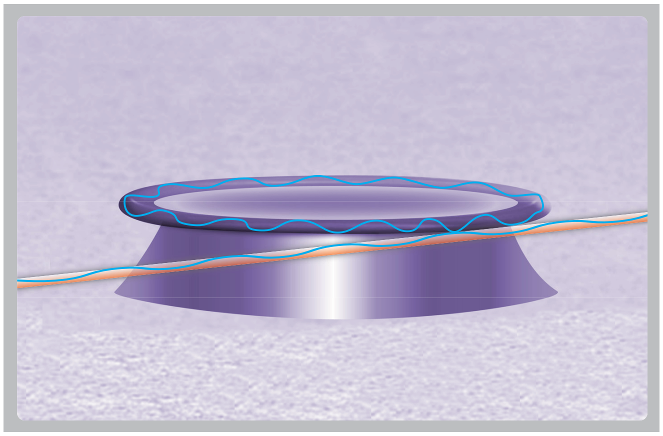
Need a wavelength or tuning range that you do not see? Smoother linearity or a tighter linewidth? Let us know, these are the real-life challenges we get excited about trying to solve.

We still know that good engineering requires an in-depth knowledge of our customers, their visions and problems, and how technology can make their applications really work. And we still want to have fun helping researchers do the best science they can.

Talking face to face is great so let us know if you are going to be in the Silicon Valley. We would love to show you around our new facilities, or just drop by our booth at a trade show or conference.

We look forward to hearing from you.

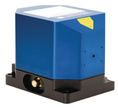
On the Cover



The toroid microresonator is an intriguing photonic device that can be used to confine and store light for up to hundreds of nanoseconds. As with many other optical microresonators, the toroid can be fabricated on Si ("on-chip") from glasses, polymers, and III-V binary semiconductors. The image shows an artistic rendition of a toroid microresonator being resonantly excited by light at a blue wavelength propagating through the optical fiber waveguide. The toroid is sensitive to its environment and has been proven to work in biological and particle sensing; it has been used as a microlaser because of the large light intensity that can be built up in its ring; it has also been used to generate a frequency comb spanning hundreds of nanometers. Indeed, this versatile on-chip device continues to be the focus of much research, has found myriad applications, and therefore demands Simply Better™ Photonics.

New Focus Application Guide

New Focus lasers and optical amplifiers are used by top scientists and engineers around the world, both in lab and industry, in a variety of cutting edge applications.

Applications	Series	Available Wavelengths	Tuning Range
• Fiber-Bragg sensing • Spectroscopy • Telecom test and measurement • Metrology	 TLB-6600 Venturi™ Swept-Wavelength Tunable Lasers	835-1630 nm	**Swept Wavelength Wide Mode Hop Free Tuning**
	 TLM-8700 OEM Tunable Laser Modules	835-1630 nm	
• Spectroscopy • Microcavity Resonators • Nitrogen Vacancy Centers (NV-Centers) • Sensing	 TLB-6700 Velocity™ Widely Tunable Lasers	635-1630 nm	**Wide and Fine Mode Hop Free Tuning**
• Atom cooling • Magneto-optical Traps • Bose-Einstein Condensates • Atomic Clocks	 TLB-7100 Vantage™ Tunable Diode Laser	392-867 nm	**Wide Tuning and Mode Hop Free fine tuning**
• Interferometry • Metrology • Atomic Clocks • Atom cooling, trapping and BEC	 TLB-6800 Vortex™ Plus Tunable Lasers	455-1630 nm	**Mode Hop Free Precision Fine Tuning**
• Laser Cooling • Magneto-optical Traps • Bose-Einstein Condensates • Optical Amplification of CW sources	 TA-7600 VAMP™ Tapered Semiconductor Amplifiers	755-920 nm	**Fixed Wavelength**
• Raman spectroscopy • Interferometry • Terahertz generation • Data encryption • LIDAR	 SWL-7500 Single Wavelength Diode Lasers	633-1610 nm	

Tunable External Cavity Diode Lasers

Tunable External Cavity Diode Lasers (ECDLs) are employed in many applications, including coherent optical telecommunications, atomic and molecular laser spectroscopy, laser cooling, atomic clocks, environmental sensing, and optical microcavities. In addition to tunability, these applications often require narrow linewidth single mode operation. Semiconductor diode lasers typically operate with several longitudinal modes lasing simultaneously, leading to low coherence and large linewidths. One method of extracting highly coherent light from a semiconductor-based laser requires that you anti-reflection (AR) coat the diode so it acts only as a gain element. The diode can then be placed in an external cavity that contains wavelength-selective optics so that only a single mode lases at any given time.

To enable tuning across the diode gain band two configurations, Littrow and Littman-Metcalf, are typically employed. These utilize a grating to provide optical feedback into the diode chip, as illustrated in Figure 2. In the Littrow design, mode is selected by rotating the diffraction grating. In the Littman-Metcalf design, the grating remains fixed and mode selection occurs by rotation of an additional mirror in the cavity.

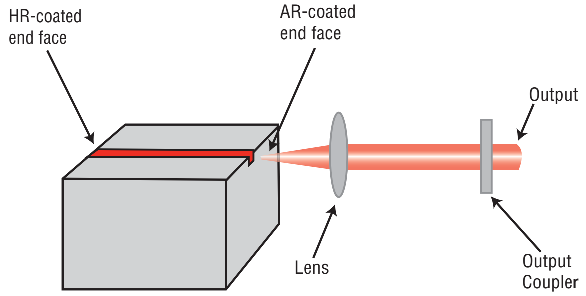


Figure 1. Laser diode placed into an external cavity.
The anti-reflection coating prevets the diode fron self lasing

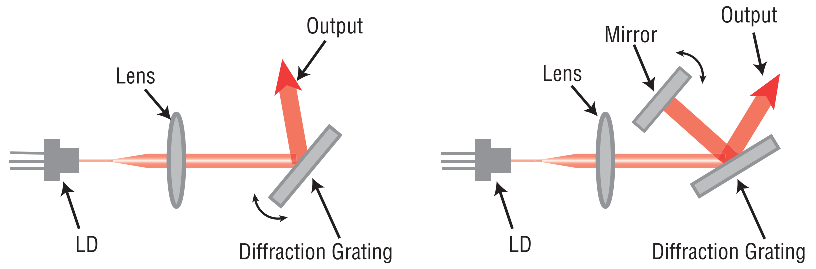


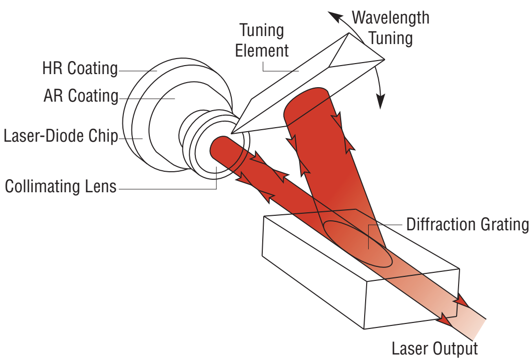
Figure 2: Tunable external-cavity diode lasers in Littrow and Littman-Metcalf configuration

Littman-Metcalf vs. Littrow Configurations

There are advantages and disadvantages to both the Littman-Metcalf and Littrow cavity designs. In general, the Littrow design results in higher output laser power; however, advances in chip manufacturing technology and optical coatings have led to higher power Littman-Metcalf ECDLs. The optical feedback in a Littrow is much stronger and high quality AR coatings on the diode facet, which can be challenging, are not critical as it is for the Littman-Metcalf design. Therefore, many diodes, specifically the blue and other exotic wavelengths can be incorporated into a Littrow cavity and not in a Littman-Metcalf cavity. The Littman-Metcalf achieves mode-hop-free tuning ranges in the 10s to 100s of nanometers and the Littrow typically has less than a tenth of a nanometer mode-hop-free tuning.

Mode-hop-free Wide Tuning New Focus Lasers

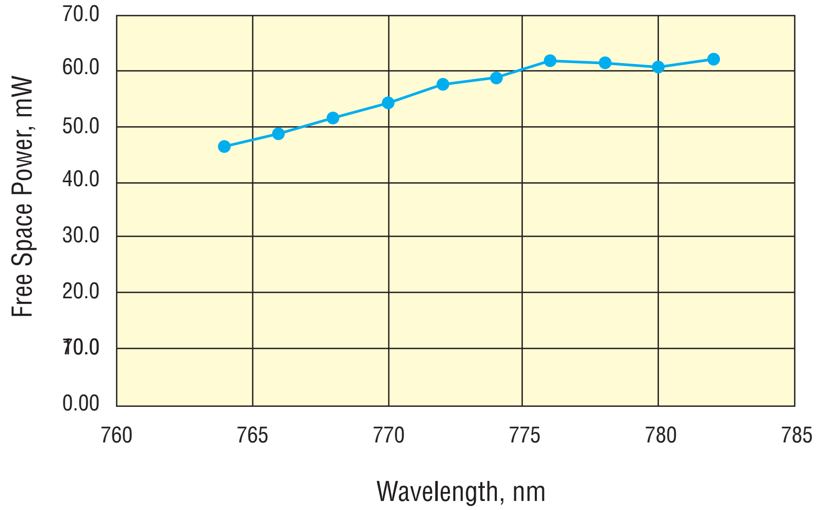
True single-mode tuning requires that the optical feedback be dominated by the external optics and not by reflections from the diode facet. We use AR-coated diodes to reduce residual diode reflectivities to below 0.001 which guarantees single-mode operation.



A modified Littman-Metcalf *configuration.*

We place the diode in an external laser cavity that is based on a modified Littman-Metcalf configuration. In this cavity, a grazing-incidence diffraction grating and a tuning element provide all the necessary dispersion for single-mode operation. The amplitudes of non-lasing modes are suppressed to 40 dB below the lasing mode.

The wavelength in a modified Littman-Metcalf laser is changed by tilting the retroreflector, which changes the diffracted wavelength fed back into the cavity. To prevent mode hopping, the cavity length must be kept at a constant number of wavelengths as the laser tunes. This requires that the pivot point around which the element tilts be positioned with sub-micron accuracy. Using a patented pivot-point location technique, we produce lasers with truly continuous, mode-hop-free tuning across tens of nanometers.



Wide, Mode-hop-free tuning of the Model TLB-6728 *Velocity*

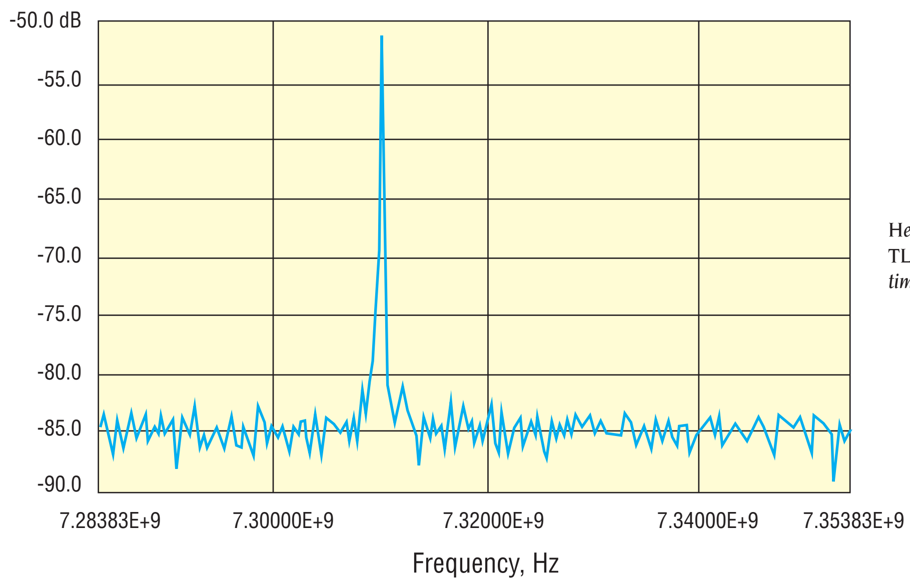
Which laser configuration is right for my application?

When your application calls for wide mode-hop-free tuning, high stability, and hands-off ease of use, select the Littman-Metcalf. When the wavelength you need is not available in a Littman-Metcalf or you need higher power without wide mode-hop-free wide tuning, select the Littrow.

Linewidth and Frequency Stability

Once single-mode operation is established by the optics in the external cavity, the linewidth of the laser can be affected by acoustic coupling and cavity temperature variations, each of which can change the cavity length. It is also affected by electrical noise coupling, which causes changes in the index of refraction of the diode and in the piezo length (also affecting the cavity length). Since various noise contributions occur on different timescales (thermal > acoustic > electrical), the length of time over which a linewidth measurement is taken is important. Representative linewidths are measured over milliseconds.

Linewidth as a Function of Integration Time



Heterodyne beat note of two Velocity TLB-6712 *lasers,* 50 *ms integration time. Deconvoluted* FWHM <200 *kHz.*

What is meant by instantaneous linewidth?

Besides the time dependent jitter component in the linewidth, the timeless intrinsic linewidth is determined by the cavity design. This can be measured by heterodyning on a very short time scale (less than 1 ms) with a real-time spectrum analyzer or with any spectrum analyzer by matching the resolution bandwidth to the laser linewidth. The signal strength on the spectrum analyzer will only drop if the resolution bandwidth is smaller than the heterodyned signal.

Wavelength Drift

LB1005 *Servo Controller*

Longer time wavelength drifts (over seconds) of narrow-linewidth tunable lasers occur due to floor vibrations, small temperature drifts, and even acoustic noise from people talking in the vicinity of the laser. The "free-running" linewidth, or short-term stability of the laser, is often not adequate for many applications without active stabilization of the laser frequency. The wavelength can be stabilized by using feedback control of the tuning element. In order to do this, an optical reference such as a gas cell or high finesse optical cavity is used to provide feedback to the piezoelectric transducer (piezo) that controls the grating or tuning arm to shift the laser wavelength so that it remains fixed to the stable resonance line shape of the reference, regardless of external perturbations.

The Philosophy of New Focus Lasers

New Focus lasers are designed to be complete and easy-to-use systems.

Complete Systems

New Focus laser systems are plug-and-play, fully-functioning systems which include active current drive and closed loop temperature control.

TLB-7100 *Vantage Laser and* TLB-6800-LN *Controller.*

Laser Head Recognition

For systems with modular laser heads and controllers, critical diode settings, mximum current and optimum temperature are stored in the laser head. These critical parameters are determined and set at the factory during the build of each individual laser unit. The corresponding controller calls this information from the laser head on startup ensuring top performance.

Safety Features

The critical settings stored in the laser head prevent fatal damage to the tunable laser system, particularly to the laser diode or tapered amplifier chip. The preset maximum current value prevents the user from delivering too much current. Each tapered amplifier has a safety shutoff feature that is enabled when the seed drops below a safe power.

Design

Over the decades, New Focus has accumulated vast ECDL engineering and production know-how. This knowledge shows in our design.

- Mechanical design, including Star-Flex™ actuation and magnetic damping reduce vibrational noise.
- Heavy housing and thermal insulation for temperature and acoustic isolation.
- Low noise control electronics for narrower linewidths.

What is Magnetic Damping?

The New Focus Velocity, Vortex Plus, and Vantage Lasers incorporate patent pending magnetic damping to improve laser stability. External vibrations coupled into the laser cavity can excite the natural mechanical frequencies of the laser tuning arm. A magnet is placed behind the tuning arm to dampen the amplitude of these unwanted vibrations that lead to laser frequency instability and linewidth broadening.

TLB-6700 Velocity™ Widely Tunable Lasers

- Guaranteed mode-hop-free tuning across entire tuning range
- Coarse and fine wavelength control
- Internal permanent fiber coupling
- Armored output fiber
- LabVIEW control available

Select the Velocity for applications requiring wide (many nanometers) mode-hop-free tunability.

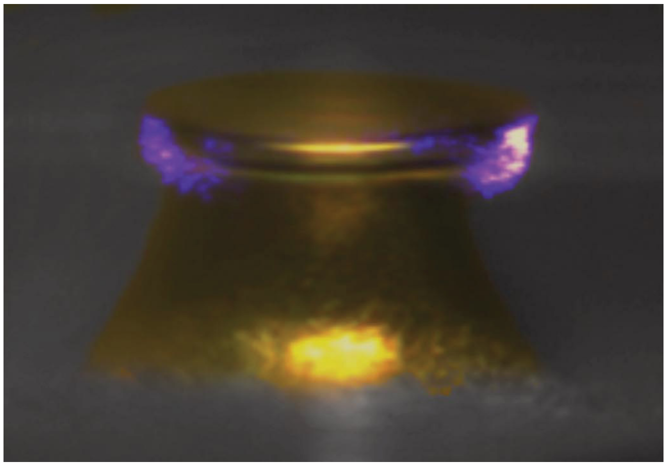


Photo courtesy of Ashley Maker, Andrea Armani lab, University of Southern California.

Microtoroid Resonators (top image) are photonic devices capable of confining and storing light for up to several hundred nanoseconds. Laser light propagating through a tapered optical fiber waveguide is evanescently coupled into a microtoroid initiating a second, longitudinally propagating wave through the rim of the microtoroid. The image, obtained in the lab of Prof. Andrea Armani (USC), shows light at 410 nm being evanescently coupled into a silica microtoroid. These longitudinal Whispering Gallery Modes (WGMs) can be used as probes of the microtoroid's environment.

Optomechanical Modal Spectroscopy (OMMS) (bottom image) of the natural vibrations of on-chip micron-scaled spheres is described by Tal Carmon (U of Michigan) and Kerry J. Vahala (Caltech) (Phys. Rev. Lett. 2007). CW optical power evanescently coupled into these silicon spheres induces excitation of eigen-frequencies via the centrifugal radiation pressure of the optical whispering-gallery-mode. These oscillations are then monitored by measurement of the modulated transmitted power. Perturbations in these structures result in degeneracy splitting of the vibrational modes, analogous to Stark splitting of atomic and molecular excited states.

The New Focus Velocity Widely Tunable Laser delivers mode-hop-free wavelength tuning for OMMS and other microcavity research, such as bio-detection and harmonic generation.

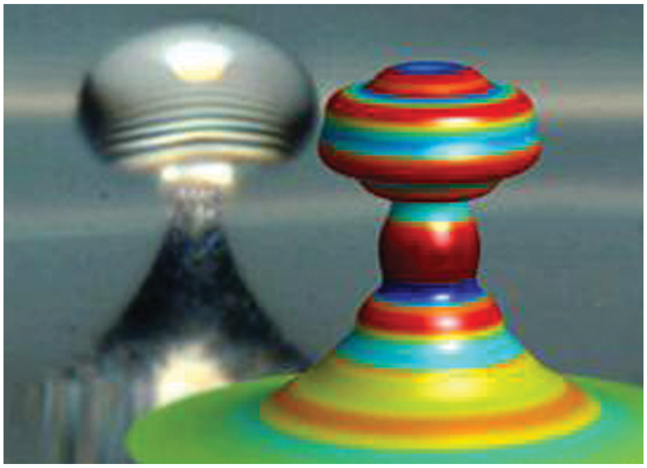
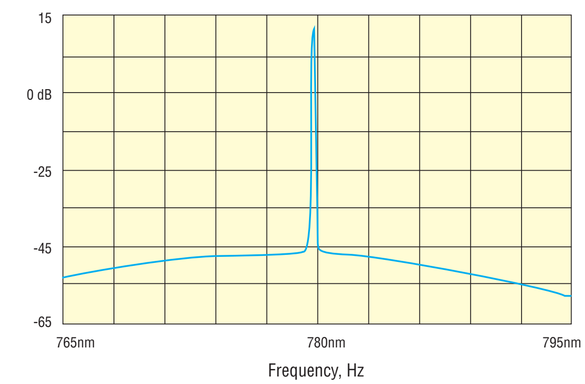
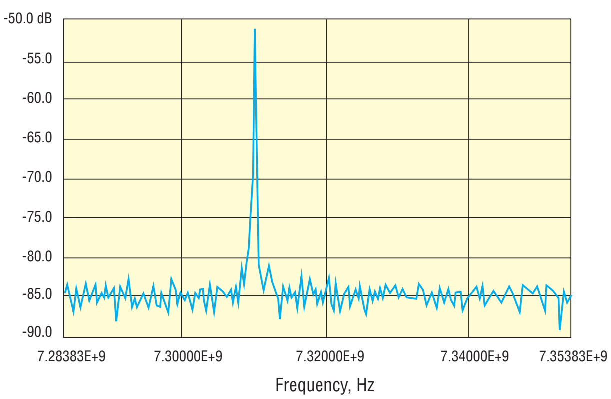


Photo courtosy of Tal Carmon (U of Michigan) in collaboration with Kerry Vahala, Caltech

At New Focus we take pride in all of our products. We are especially proud of the Velocity Widely Tunable Laser Series. The Velocity offers complete single-mode tuning across its entire specified wavelength, over tens of nanometers and a piezoelectric transducer allows for fine tuning over 50-100 GHz.

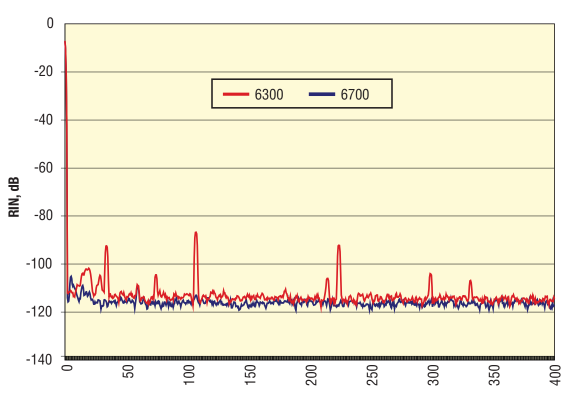


The Velocity has a side mode suppression ratio of >60dB (model dependent)

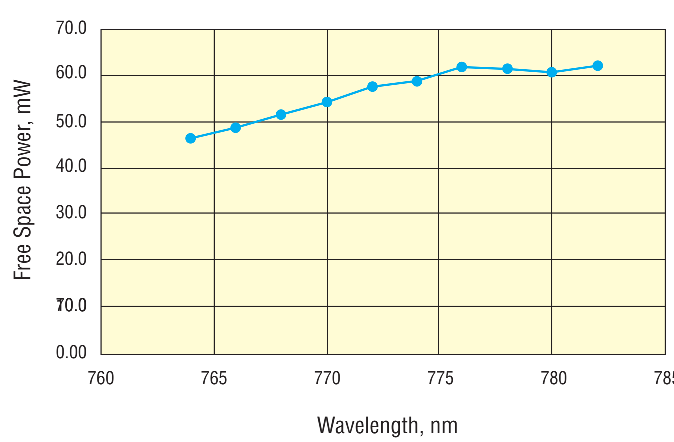


Heterodyne beat note of two Velocity TLB-6712 lasers, 50ms integration time. Deconvoluted at FWHM <200 kHz

- Huge mode-hop-free tuning range
- Motorized and Piezo control for wide scanning and fine tuning
- Higher power
- Improved stability, <200 kHz linewidth
- Integrated permanent fiber coupling



RIN test data for the Velocity 6700 and previous model Velocity 6300



Mode-hop-free tuning range of the Velocity TLB-6712

More Robust

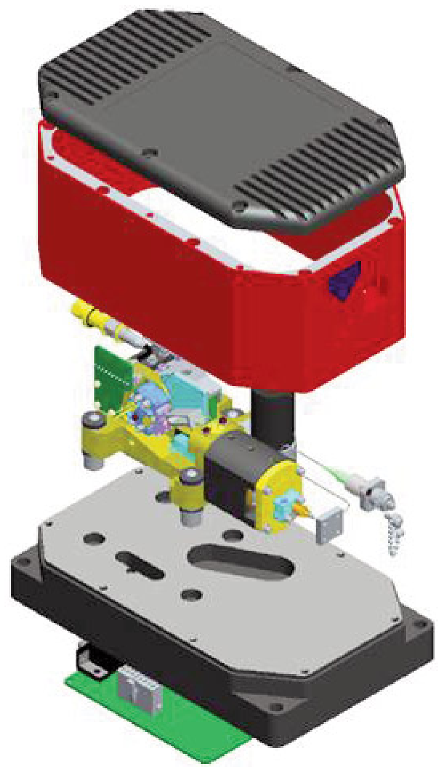
- The enlarged drop-tested and shock proof housing ensures a robust system.
- Thicker insulation increases thermal and mechanical isolation.
- Integrated optical isolator and fiber coupling eliminates fiber misalignment.
- Armored output fiber

High Power

- With a redesigned system, we are now able to incorporate thicker diodes, giving you more power to deliver to your experiments.

Low Noise

- More powerful temperature control reduces wavelength drift and power fluctuations.
- Magnetic damping stabilizes the tuning arm and reduces vibrational noise.
- A new controller delivers more current and less noise, narrowing the laser linewidth.



Mechanical schematic of the TLB-6700 *laser platform*

TLB-6700-LN Tunable Laser Controller

The 6700 Tunable Laser Controller has been engineered with direct feedback from our customers. We have increased the current to allow higher power from our lasers and reduced the noise even further for sharper linewidths and better results. The 6700 Controller monitors the Velocity lasers current, temperature, and wavelength. Each head has optimized factory settings. The 6700 Controller will read the laser's optimum settings and automatically limit the current and scan ranges to protect the laser diode cavity. Operation is simple: either from the front panel or via the USB GUI, the user can just dial up and set the desired wavelength and power. Minimum and maximum wavelengths points can be entered, and the Velocity can be set to scan back and forth between them.

TLB-6700-LN *controller*

- Higher current – 200 mA now standard
- Lower noise <250 nA RMA with 200 mA current
- Wavelength monitoring of Velocity laser head
- Complete tuning control - set a wavelength range for

multiple scans

- USB interface allows for remote user control via GUI

Velocity™ Specifications

Specifications[1]	TLB-6704	TLB-6711	TLB-6712	TLB-6716	TLB-6718	TLB-6721
Min Mode-Hop Free Tuning Range[2]	635-638 nm	729-739 nm	765-781 nm	830-853 nm	945-975 nm	1030-1070 nm
Min Mode-Hop Free Tuning Range (Fine-Frequency)	>80 GHz (110 pm)	>80 GHz (140 pm)	>80 GHz (150 pm)	>60 GHz (150 pm)	>50 GHz (160 pm)	>50 GHz (200 pm)
Free Space Power[3]	8 mW @ 638 nm	20 mW @ 737 nm	50 mW @ 780 nm	50 mW @ 850 nm	30 mW @ 960 nm	60 mW @ 1064 nm
Max Tuning Speed	5 nm/s	8 nm/s	8 nm/s	10 nm/s	10 nm/s	10 nm/s
Typical Beam Size (mm)	1.0x1.0	1.8x1.7	1.5x1.2	1.3x0.6	1.2x0.8	1.8x0.9
Linewidth (50 ms Integration Time)	<200 kHz (50 ms Integration time)					
Wide Tuning Resolution	0.01 nm					
Fine-Frequency Modulation Bandwidth	<2 kHz					
Max Current Modulation Bandwidth[4]	<1 MHz					<1 MHz
Max Current Modulation Bandwidth[5]	<100 MHz					<100 MHz

Specifications[1]	TLB-6722	TLB-6724	TLB-6725	TLB-6726	TLB-6728	TLB-6730
Min Mode-Hop Free Tuning Range[2]	1045-1085 nm	1270-1330 nm	1390-1470 nm	1470-1545 nm	1520-1570 nm	1550-1630 nm
Min Mode-Hop Free Tuning Range (Fine-Frequency)	>50 GHz (200 pm)	>50 GHz (290 pm)	>30 GHz (200 pm)	>30 GHz (210 pm)	>30 GHz (240 pm)	>30 GHz (260 pm)
Free Space Power[3]	40 mW @ 1080 nm	30 mW @ 1300 nm	45 mW @ 1450 nm	15 mW @ 1470 nm	30 mW @ 1550 nm	30 mW @ 1600 nm
Max Tuning Speed	10 nm/s	15 nm/s	15 nm/s	15 nm/s	20 nm/s	20 nm/s
Typical Beam Size (mm)	1.8x0.9	1.9x1.7	1.9x1.7	1.3x1.3	1.9x1.7	1.9x1.7
Linewidth (50 ms Integration Time)	<200 kHz (50 ms Integration time) kHz					
Wide Tuning Resolution	0.01 nm					
Fine-Frequency Modulation Bandwidth	<2 kHz					
Max Current Modulation Bandwidth[4]	<1 MHz					
Max Current Modulation Bandwidth[5]	<100 MHz					

[1]Specifications are subject to change.
[2]Contact New Focus for all available wavelength ranges.
[3]Fiber coupled and optical isolator options available.
[4]Current modulation through controller.
[5]Current modulation directly to diode through laser head SMA port.

Options	Comments
Fiber Coupled (-P)*	>30% efficiency for models 6704, 6716 >35% efficiency for model 6721, 6722 >50% efficency for models 6711, 6712, 6718, 6724, 6725, 6726, 6728, and 6730
	Permanently coupled fiber, steel jacketed
	FC/APC, PM, Panda, 1m length
Isolator (-OI)	35 dB typical isolation. 70 dB available as a custom (will include removable fiber patchcord, FC/APC, PM, panda, 1m length). Isolation may vary by wavelength. ~75% power transmission.

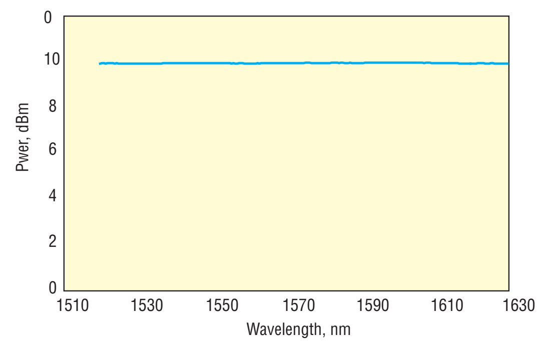
New Focus™ A Newport Company

TLB-6600 Venturi™ Swept-Wavelength Tunable Lasers

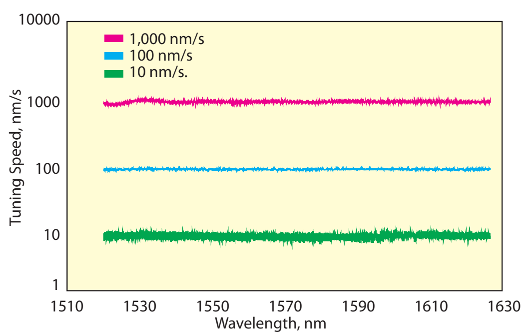
- Ultrafast 2000 nm/s tuning enables true real-time measurements
- Ultrawide 110 nm mode-hop-free tuning
- >70 dB ASE low-noise version for high-dynamic-range test and measurement
- Multiple integrated options available

Select the Venturi for applications requiring mode-hop-free wide wavelength sweeping, such as for telecom and fiber sensing.

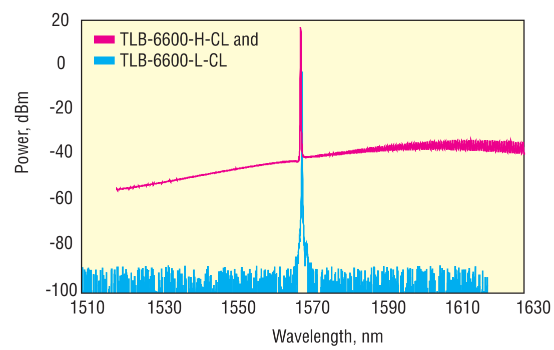
The TLB-6600 lasers deliver it all. They combine the best in tunability—ultrafast, ultrawide, and mode hop-free—with low noise, high accuracy and repeatability. Because the lasers are based on our award-winning design, they are extremely dependable with OEM-proven 24/7 reliability (over 100-million cycles tested without failure). Ideal for fiber sensing, spectroscopy, laser seeding, metrology and fiber-optics testing, these lasers are available with a variety of options so you can build the system you need.



Power stability for the Model TLB-6600-H-CL *across tuning range*



Tuning linearity for the model TLB-6600-H-CL



Carrier and ASE for Venturi models

TLM-8700 OEM Swept-Wavelength Lasers

- Ultrawide 110 nm mode-hop-free tuning
- Tuning speeds greater than 2000 nm/s
- OEM-proven reliability (>100-million cycles tested)

Just like all of our benchtop tunable lasers, these modules carry our reputation as the leading supplier of test-and-measurement tunable lasers. If you have specific needs, please do not hesitate to contact us. We want to work with you to develop a design that is right for you. The TLM-8700 OEM laser module is just one example of our OEM component portfolio. New Focus designs, develops, and manufactures custom optical solutions for a broad selection of companies in all branches of the photonics industry.

Venturi™ Specifications

Specifications[1]	TLB-6600-H-CL	TLB-6600-L-CL	TLB-6600-H-O	TLB-6600-L-O	TLB-6600-840
Mode-Hop Free Tuning Range (nm)	1520-1630 nm	1510-1620 nm	1265-1345 nm	1265-1345 nm	835-845 nm
Tuning Speed	2-2,000 nm/s	2-2,000 nm/s	2-2,000 nm/s	2-2,000 nm/s	5-1,000 nm/s
Wavelength Resetability			±15 pm		
Absolute Wavelength Accuracy	± 30 pm	± 30 pm	± 30 pm	± 30 pm	± 30 pm
Absolute Wavelength Accuracy (with PWR option)			<1 pm		
Output Power (fiber-coupled)	>6 mW	>1 mW	>4 mW	>1 mW	>3 mW
Output Power Flatness (swept)			>50 dBc		
ASE	>40 dB	>70 dB	>40 dB	>70 dB	>40 dB
Integrated Dynamic Range	>15 dB	>55 dB	>15 dB	>55 dB	N/A
Fiber Optic Connector			FC/APC		
Fiber Type	SM or PM	SM or PM	SM	SM	SM
Integrated Options Available[2]	PWR, VOA, PC, RM	PWR, VOA, PC, RM			

1. Specifications are subject to change.
2. PWR - Precision Wavelength Reference, VOA - Variable Optical Attenuator, PC - Polarization Controller, RM - Rack Mount. Contact New Focus for futher details.

Options

Integrated Precision Wavelength Reference Module

Accuracy	<1 pm
Repeatability	<1 pm
Insertion Loss	1.0 dB (max)
Polarization Dependent Loss (PDL)	0.1 dB (max)
Valid Sweep Rates	10–200 nm/s
Wavelength Range Excluded	None
Fiber Type (input/output)	SM/SM
Model	TLB-6600-PWR

Wavelength Reference option available for CL version only.

Integrated Polarization Controller, 6-State

SOP Generated	6-SOP: -45°, 0°, 45°, 90°, RHC, LHC
SOP Repeatability	±1° on Poincaré sphere
SOP Switching Speed	250 ms
Rotation Angle Wavelength Dependence	0.068°/nm
Insertion Loss	1 dB (typical)
Insertion Loss Variation with SOP	0.1 dB (max)
Insertion Loss Variation with Wavelength	0.2 dB (max)
Fiber Type (input/output)	PM/SM
Model	TLB-6600-PC

Polarization Controller option available for the CL version. When ordering the integrated Polarization Controller (-PC) option, you must also order a Polarization Maintaining fiber output (-PM) to couple the light to the -PC. The final output will be from a single-mode (-SM) fiber.

Integrated Variable Optical Attenuator

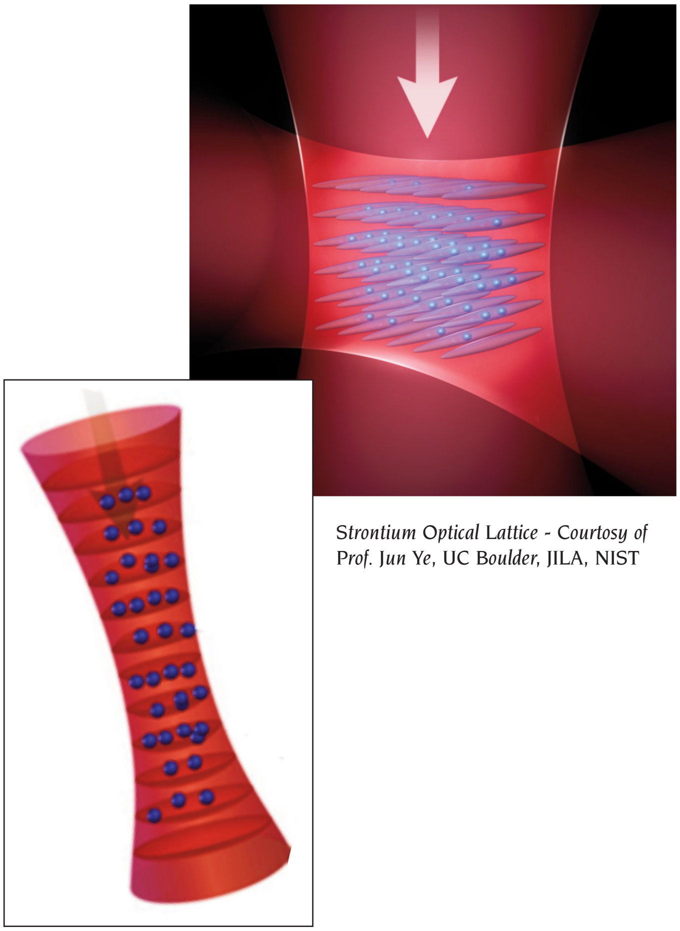
Attenuation Range	>20 dB
Accuracy	0.1 dB (typical across range)
Excess Loss	<0.7 dB (max)
Polarization Dependent Loss (PDL)	0.2 dB (max)
Fiber Type (input/output)	SM/SM
Model	TLB-6600-VOA

Gain and P-I corner are independently adjustable.

TLB-6800 Vortex™ Plus Tunable Lasers

- Exceptional ease of use
- Wide mode hop free tuning
- Direct diode access for high RF speed modulation
- Widest mode-hop-free piezo tuning of any commercially available tunable ECDL including blue wavelengths
- Star-Flex Actuation of the tuning arm for maximum stability
- Function generator built into the TLB-6800-LN controller

Select the Vortex Plus when extremely stable and wider piezo tuning is required such as for precision spectroscopy, laser physics, and interferometry.



Strontium Optical Lattice - Courtosy of Prof. Jun Ye, UC Boulder, JILA, NIST

The strontium optical lattice clock at JILA works by referencing an ultra-stable clock laser to laser-cooled and trapped strontium atoms. Strontium is one of nature's highest-Q frequency references, with a quality factor of 1018. This clock takes advantage of the lower quantum projection noise of a many-body quantum system to achieve new records in clock precision, stability, and total systematic uncertainty. To prepare the atoms for precision spectroscopy, they are first laser-cooled using light from 461 nm blue diode lasers. Then, after a second red laser cooling stage, the atoms are loaded into an optical lattice, where they are trapped in standing waves of light. The clock laser is then used to perform coherent spectroscopy. The blue light is used again to measure the number of atoms in the ground and excited states via fluorescence. This allows us to measure the laser frequency against the atomic resonance.

Precision Tunable Laser Evolution of Excellence

1996

Vortex™

Introduced in 1996 the Vortex 6000 Series Tunable Lasers offered narrow-linewidth and low-noise performance built to our customer's wavelength specifications. Based on a proven monolithic design, there were no adjustable components that could become misaligned over time. The laser cavity and drive electronics were designed to provide maximum frequency-modulation capabilities, allowing for modulation above the frequency of mechanical-noise sources.

2004

Stablewave™

In 2002, New Focus partnered with NASA's Jet Propulsion Laboratory (Pasadena, CA) to develop the next generation atomic clocks for microgravity measurements and GPS space deployment, as part of an experiment to test many of the predictions of Albert Einstein's Theory of Relativity. New Focus proudly released the Stablewave 7000 Series in 2004. To deliver truly reliable performance, these lasers used an exceptionally rugged, patented laser cavity.

2008

Vortex™ II

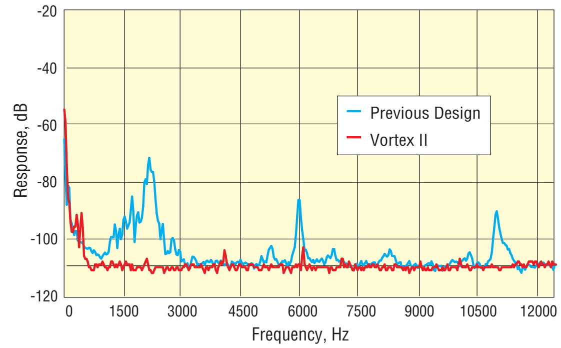
The New Focus engineering team was once again asked to provide the next level of laser performance that would help the atomic spectroscopy community and others by providing low frequency jitter and low drift mode-hop-free tunable laser. The Vortex II 6900 Series, the third-generation fine tuning ECDL design released in 2008, was even more resistant to acoustical and mechanical perturbations than its predecessor. The technical challenge came down to stiff rotational motion without translation. It was under this mandate that Star-Flex motion actuation and the patented technique of magnetic damping were born.

2012

Vortex™ Plus

The Vortex Plus is the latest addition to the New Focus line of Finely Tunable Littman-Metcalf Lasers. Conserving the same robust cavity and StarFlex actuator, New Focus has adapted the Vortex II to accept longer diode chips, resulting in significantly higher output power. The Vortex Plus operates with our low noise TLB-6800-LN laser controller, reducing the laser linewidth from 300 kHz to 200 kHz. Also, an SMA port for direct diode current modulation has been reintroduced to the Vortex Plus, enabling up to 100 MHz high speed modulation.

Star-Flex actuator design of the TLB-6800 Vortex Plus laser.



Frequency responce of Vortex II in compareson with original Vortex (100 dB white noise test). The Vortex II has improved stability due to the Star-Flex design and magnetic damping.

The Star-Flex design was engineered to be robust enough to withstand a space shuttle launch environment and operate for years in space. The design had to pass strict tests to meet the requirments for space readiness. You can see just how much of a difference the new design made to the RIN test of the Vortex laser in the above plot.

TLB-6800-LN Low Noise Controller

- Interchangeable laser heads
- High-speed current modulation
- Easy frequency modulation
- Complete control of laser parameters
- Complete computer control and LanVIEW™ programs
- Detector and general-purpose input
- Built-in function generator

The Model TLB-6800-LN laser controller is designed to operate with either the TLB-6800 Vortex™ Plus Tunable Lasers or TLB-7100 Vantage Tunable Lasers. The controller allows you to easily fine tune and adjust the output power or bias current with the press of a button or, via the USB/RS-232, interface with the click of a mouse. There is no need for an external function generator to drive the piezo of your tunable laser with the built in function generator. The TLB-6800-LN controller has easy to access front panel controls, digital interface, and real buttons to make your lab life easier.

Vortex™ Plus Specifications

Specifications[1]	TLB-6802-455	TLB-6802	TLB-6804	TLB-6811
Available Wavelengths[2]	455-457 nm	459-461 nm	632.5-640 nm	725-741 nm
Min Mode-Hop Free Tuning Range (Fine-Frequency)	>25 GHz	>25 Ghz	>140GHz	>100 GHz
Free Space Power	40 mW @ 455 nm	40 mW @ 461 nm	4 mW @ 633 nm	20 mW @ 737 nm
Linewidth (50 ms Integration Time)	200 kHz			
Fine-Frequency Modulation Bandwidth	>100 Hz (100 GHz Amplitude) >1.5 kHz (>20 GHz Amplitude)			
Max Current Modulation Bandwidth	<1 MHz			
Options[3]	Custom Wavelengths, Free-space, Optical isolator, Fiber-coupled			

Specifications[1]	TLB-6813	TLB-6814	TLB-6817	TLB-6818
Available Wavelengths[2]	765-781 nm	794-806 nm	838-853 nm	890-910 nm
Min Mode-Hop Free Tuning Range (Fine-Frequency)	>100 GHz	>100 GHz	>90 GHz	>90 GHz
Free Space Power	50 mW @ 780 nm	30 mW @ 795 nm	40 mW @ 852 nm	15 mW @ 895 nm
Linewidth (50 ms Integration Time)	200 kHz			
Fine-Frequency Modulation Bandwidth	>100 Hz (100 GHz Amplitude) >1.5 kHz (>20 GHz Amplitude)			
Max Current Modulation Bandwidth[4]	<1 MHz			
Options[3]	Custom Wavelengths, Free-space, Optical isolator, Fiber-coupled			

Specifications[1]	TLB-6820	TLB-6821	TLB-6824	TLB-6828
Available Wavelengths[2]	950-980 nm	1030-1085 nm	1270-1330 nm	1520-1630 nm
Min Mode-Hop Free Tuning Range (Fine-Frequency)	>80 Ghz	>60 GHz	>60 GHz	>50 GHz
Free Space Power	12 mW @ 960 nm	60 mW @ 1064 nm	5 mW @ 1300 nm	20 mW @ 1550 nm
Linewidth (50 ms Integration Time)	200 kHz			
Fine-Frequency Modulation Bandwidth	>100 Hz (100 GHz Amplitude) >1.5 kHz (>20 GHz Amplitude)			
Max Current Modulation Bandwidth[4]	<1 MHz			
Options[3]	Custom Wavelengths, Free-space, Optical isolator, Fiber-coupled			

[1]Specifications are subject to change.
[2]Contact Newport for all available wavelength ranges.
[3]Fiber coupled and optical isolator options available.

Options	Comments
Fiber Coupled (-P)*	>30% efficiency for models 6804, 6814, 6817, 6820, >35% efficiency for model 6818, 6821 >50% efficency for models 6811, 6813, 6818, 6824, 6828 FC/APC, PM, Panda, 1m length
Isolator (-OI)	35 dB typical isolation. 70 dB available as a custom (will include removable fiber patchcord, FC/APC, PM, panda, 1m length). Isolation may vary by wavelength. ~75% power transmission.

TLB-7100 Vantage™ Tunable Diode Laser

- Tuning arm window allows you to effortlessly return to your desired wavelength
- Lowest wavelengths of any commercially available ECDL
- Piezo fine-tuning and manual coarse-tuning to access the entire diode gain band
- Feed Forward for extended mode-hop-free tuning
- TLB-6800-LN Controller with built-in function generator

Select the Vantage when blue and exotic wavelengths or higher power are needed for atomic spectroscopy.

BLUE

Contact us for blue wavelengths from 369 nm+

The Vantage adopts the Littrow design to offer higher power at a variety of wavelengths to meet your experimental needs. Each laser unit is optimized at a user-specified wavelength to provide top performance and mode-hop-free piezo tuning while providing the option to manually coarse tune to another wavelength within the diode gain band. The Vantage laser comes standard with our new low noise TLB-6800-LN controller. The TLB-6800-LN feed forward capability, sometimes necessary to extend the mode-hop-free tuning range in a Littrow cavity. New Focus Vantage… Simply Better Littrow™.

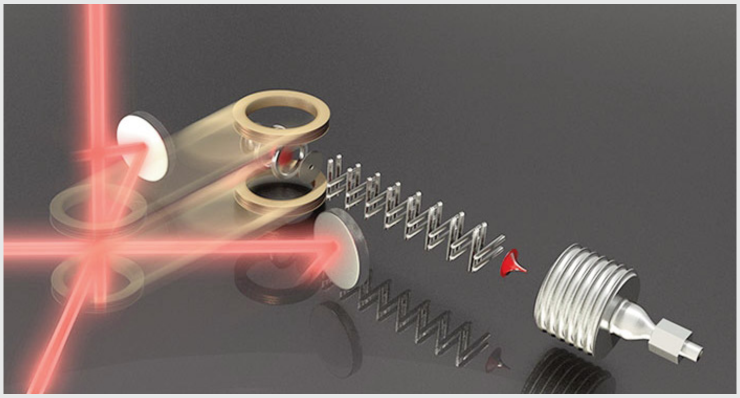
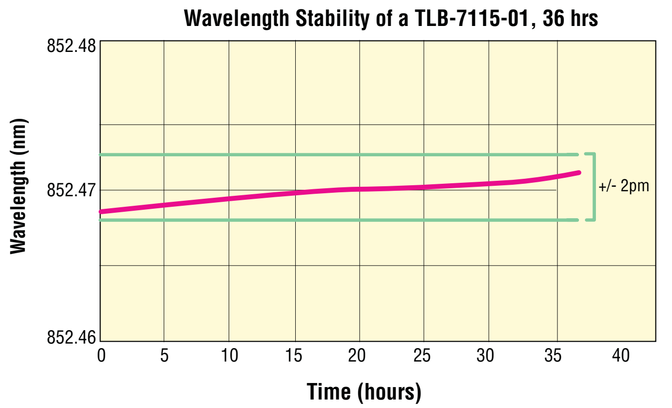


Photo courtesy of Heather Lewandowski. Credit: Brad Baxley, JILA

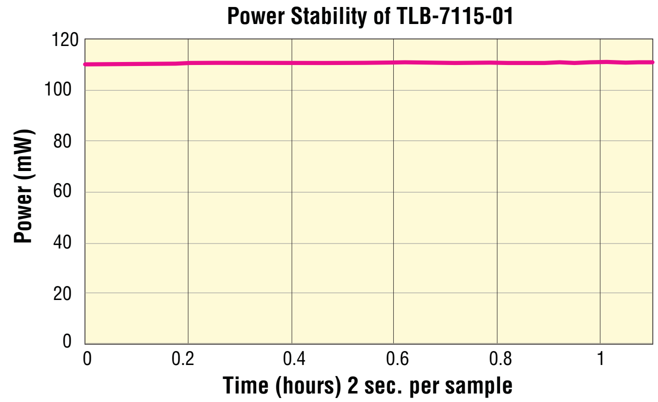
I Sing the Body Electric: Experimental setup for studying the collisions of ultracold Rb atoms with cold ND3 molecules at the Lewandowski Group at JILA. The atoms are cooled and trapped at the intersection of the (red) laser beams. A beam of cold ND3 molecules is created by the pulsed valve at the lower right, then slowed and trapped by metallic rings and rods. Collisions occur when the atom trap is moved to overlay the molecule trap. According to theory, in the absence of an electric field, ND3 molecules will be mostly unaffected by collisions. (bottom panel) Experimentally, electric fields increase the likelihood that collisions will cause an ND3 molecule to flip inside out and change its quantum state.

Model Number	TLB-7102-01	TLB-7102-02	TLB-7113-01	TLB-7115-01
Wavelength Tuning Range[2]	392 - 398 nm	421 - 423 nm	765 - 782 nm	830 - 867 nm
Typical Mode-Hop Free Tuning	10 GHz with feedforward 2 GHz without feedforward	5 GHz with feedforward 2 GHz without feedforward	50 GHz	50 GHz
Typical Power	15 mW @ 397 nm	10 mW @ 423 nm	90 mW @ 780 nm	90 mW @ 852 nm

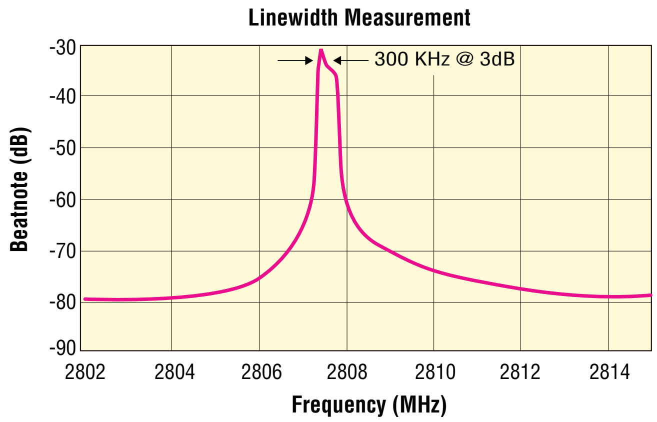
1. Published specifications at the time of order are guaranteed. The Vantage is serviceable both at the factory and on-site. Specifications are guaranteed when factory built and serviced only.
2. Laser is optimized at your specified wavelength. Please indicate desired wavelength to 0.01 nm.
3. Laser can be coarse tuned across diode gain band. Contact New Focus for more information.



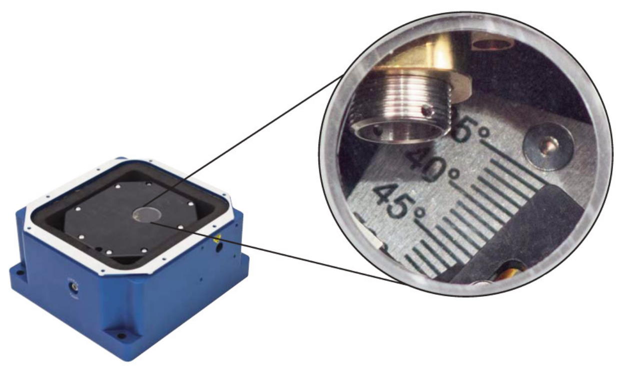
Measured using a wavemeter with a 1pm resolution. Laser is free-running



Power measurment of a TLB-7115-01 Vantage at 852 nm



Heterodyne beat note of two Vantage lasers, integrated over 50ms



Angle viewing window

Vantage™ Specifications

Specifications[1]	Value	Comment
Linewidth	300 kHz	Integrated over 50 ms
Wavelength Stability	1 pm 5 pm	Over 1 hour Over 36 hours
Modulation Frequency	>100 Hz >1.5 kHz	100 GHz amplitude >20 GHz amplitude
Max Current Modulation Bandwidth	<1 MHz	Through controller
Max Current Modulation Bandwidth	<100 MHz	Directly to diode through laser head SMA port
Optical Output	Free-space	

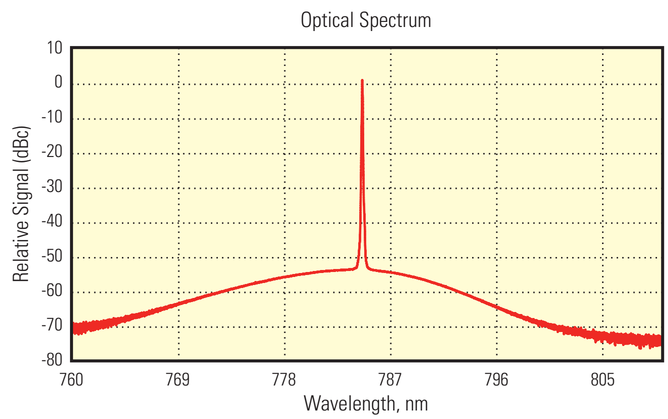
TA-7600 VAMP™ Tapered Amplifier

- Fiber coupled input ensures fast, easy, and reliable alignment
- Active input power monitoring ensures that self-lasing will not damage the tapered amplifier chip
- Use your Vortex Plus or your own seed for a complete MOPA system
- Optical isolation of the amplifier output standard on all models

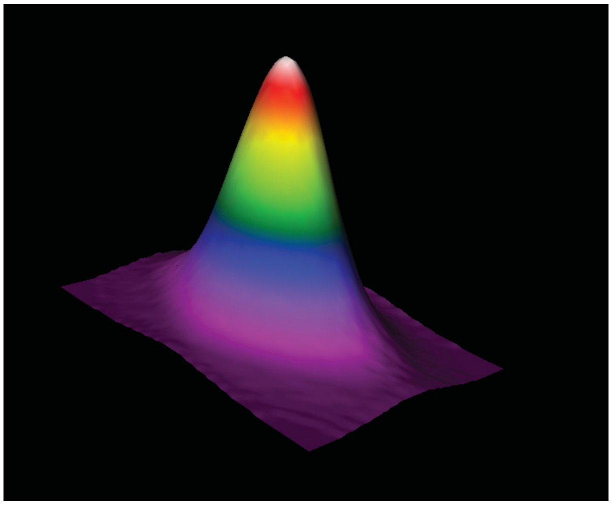
Select the Tapered Amplifier when your experiment demands higher power, such as laser cooling

The typical output power of an ECDL laser can often range from 10-100+ mW. Numerous applications, however, require even higher laser power. In these special cases a tapered optical amplifier can be used to directly amplify the output of the ECDL, without first having to convert it to an electronic signal, and can typically yield 2+ W of output power. Semiconductor tapered amplifier chips are available for a large range of wavelengths. Alignment into the front facet of the chip is critical for performance and can be a pain-staking process. Here, at New Focus we have circumvented this process by introducing a fiber-coupled FC/APC input port. Our team of engineers have also integrated many key features that make optical amplification and power stability something you can now take for granted, keeping your mind on the science and not your laser power.

ColdQuanta's innovative BEC system is designed to streamline and simplify the production of ultracold atoms and BECs. At the heart of the system is the RuBECi® where rubidium atoms are cooled to temperatures of below 1 μK, trapped, and manipulated inside the vacuum cell. A New Focus Tapered Amplifier is used to provide ample power for laser cooling and manipulation of the atoms.

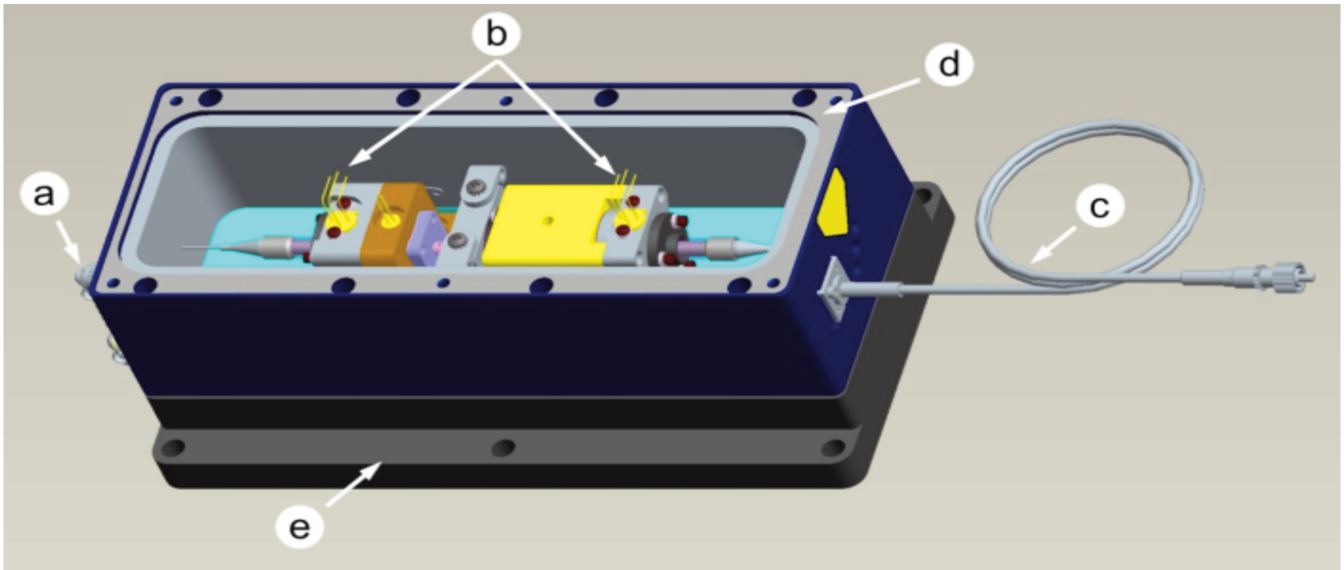


The VAMP *features extremely high* ASE *rejection to improve your signal-to-noise.*


Beam profile at 60cm

FC/APC *input connector on the* VAMP TA *makes alignement a snap.*

Every New Focus tapered amplifier includes an FC/APC input fiber connection. This allows for the seed input to be coupled into an internal fiber that has been carefully pre-aligned to the tapered amplifier diode ensuring reliable and trouble-free alignment – every time. Two onboard photodiodes are used to monitor the input and output powers. Active input power monitoring helps prevent damage to the tapered amplifier chip through self-lasing at low seed power. Active output power monitoring helps ensure a long-term output power stability with excursions no greater than about 1%. The amplified output can be fiber coupled, although free-space option is available.



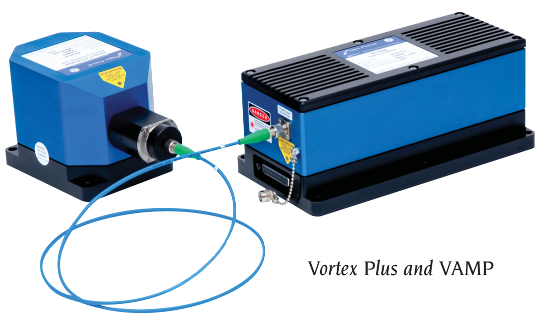
The figure above shows a 3-D model of a New Focus™ TA-7600 VAMP Tapered Amplifier. Some key features of the VAMP TA are labelled in the figure. On the left is the FC/APC input fiber connection (a), which is standard with all of our New Focus TAs. This couples the input into a fiber that has been prealigned with respect to the tapered amplifier diode. This ensures reliable and trouble-free alignment – every time. The input and output power are monitored using two photodiodes (b). The output can be fiber coupled (c) although free space option is available. On the output side, a 35 dB isolator comes standard with every amplifier. Fluctuations in the temperature of the tapered amplifier diode can affect its performance adversely, therefore temperature control is critical. To this end, thermal insulation is achieved by wrapping foam on the inside of the amplifier housing (d). In addition, the base (e) of the tapered amplifier housing acts as a heat sink.

The VAMP TA is controlled using the TA-7600-LN Controller. Full control is made possible through the easy-to-use front panel interface. In addition, full control is also available using the USB or RS232 communication ports on the rear panel. Through the controller you can monitor the tapered diode temperature by way of a temperature sensor mounted on the diode block. Thermoelectric coolers are used to control the temperature of the diode.

VAMP™ Specifications

	TA-7612	TA-7613	TA-7613-H	TA-7614	TA-7614-H	TA-7616	TA-7618
Wavelength Range (nm)[1]	755-775	775-785	779-790	787-810	787-805	825-855	910-920
Center Wavelength (nm)	765	780	780	795	795	850	915
Max Output Power[2]	>1.5 W	>1 W	>2 W	>0.5 W	>1.8 W	>1 W	>1 W
Output Power (fiber-coupled)[3]	> 0.5 W	> 0.5 W	N/A	>0.25 W	>0.25 W	> 0.5 W	N/A
Beam Divergence (mrad)	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5
Min Input at FC/APC Connector	See Comments Below[3]						
Beam Pointing Stability	<50 µrad (±2°C)						
ASE (at maximum power)	<-45 dB (0.01 mm OSA resuolution)						
Long Term Stability (Power, closed loop)	<2%						
Operating Temperature Range (°C)	15-30						
Max Input at FC/APC Connector	100 mW						
Linewidth	Seed Laser Dependent						
Frequency Jitter	Seed Laser Dependent						

[1]The TA-7600 series of Tapered Amplifiers is available at many wavelengths. If you do not see your target wavelength, please contact your regional sales manager or representative for further information.
[2]At Center Wavelength. Contact factory for power at your specific wavelength. Specifications (other than output power) are when seeded by a New Focus Vortex II or Velocity laser. Minimum fiber-coupled seed power is required to reach specified output power. All specifications subject to change without notice.
[3]Minimum seed power is 30 mW for TA-7608 (300 mW output power is achieved with a 9 mW Vortex II seed laser), 15 mW for TA-7612, TA-7616, TA-7614, 20 mW for TA-7613, TA-7613-H and 10 mW for TA-7618 to achieve full specified power output. The tapered amplifier has a safety shutoff feature, activated below 5 mW, that prevents damage to the tapered chip.



Vortex Plus and VAMP

Seeding the VAMP

When seeded with a low-ASE source such as the Vortex Plus or Velocity lasers, the VAMP faithfully reproduces the narrow linewidth and high contrast ratio. The VAMP will also accept other seed sources, including many homemade ECDLs. Remember that the VAMP requires fiber coupled input to consistently ensure precise alignment.

Velocity and VAMP

Create Your All New Focus MOPA

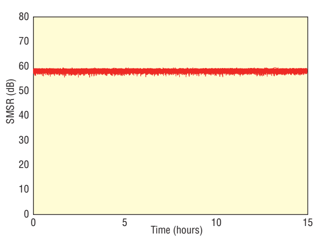
New Focus offers a complete solution to create your MOPA (Master Oscillator Power Amplifier), giving you the power you need for your atomic spectroscopy, laser cooling, and BEC experiments.

Atom	Seed Laser	Amplifier	Power	λ
K	TLB-6813-P	TA-7612	1 W	767 nm
	TLB-6712-P	TA-7612	1 W	767 nm
Rb	TLB-6813-P	TA-7613	1 W	780 nm
	TLB-6813-P	TA-7613	2 W	780 nm
	TLB-6712-P	TA-7613	1 W	780 nm
	TLB-6712-P	TA-7613-H	2 W	780 nm
Cs	TLB-6817-P	TA-7616	1 W	852 nm

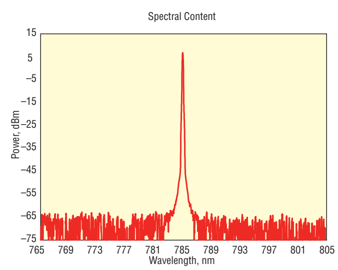
More combinations available. Contact factory for further information.

SWL-7500 Single Wavelength Diode Lasers

- Exceptional wavelength and power stability
- High coherence length perfect for interferometers
- All solid-state with a tiny footprint perfect for OEM integration
- High power at 785nm with 200kHz linewidth for precision Raman Spectroscopy



Long-term side mode suppression ratio measurement with no multimoding or mode hops.



Amplified Stimulated Emission (ASE) spectrum with low background interference and clean, unambiguous signal.

The SWL-7500 series laser offers extremely narrow linewidth in an OEM-ready platform designed for stability and longevity. This laser offers our market leading narrow linewidth in a single longitudinal mode at a single fixed wavelength. With a footprint smaller than a business card, this laser can integrate into most instrument designs with room to spare. We have carefully designed these lasers to operate continuously on a single longitudinal mode and have minimal frequency drift, making them ideal for any imaging, metrology, or spectroscopic measurements.

Specifications[1]	SWL-7504	SWL-7513	SWL-7521
Center Wavelength	633 nm	785 nm	1064 nm
Center Wavelength Stability		±1.5 pm	
Output Power	8 mW @ 633 nm	70 mW @ 785 nm	90 mW @ 1064 nm
Power Stability		<2%	
Linewidth		<200 kHz	
ASE		>-65 dBc	
Side Mode Supression Ratio		<-50 dBc	
Rated Life	>5000 hrs	>6000 hrs	>6000 hrs

1. Specifications are subject to change.
2. Please specify center wavelength to 10pm when ordering.

Accessory Products

LB1005 High-Speed Servo Controller

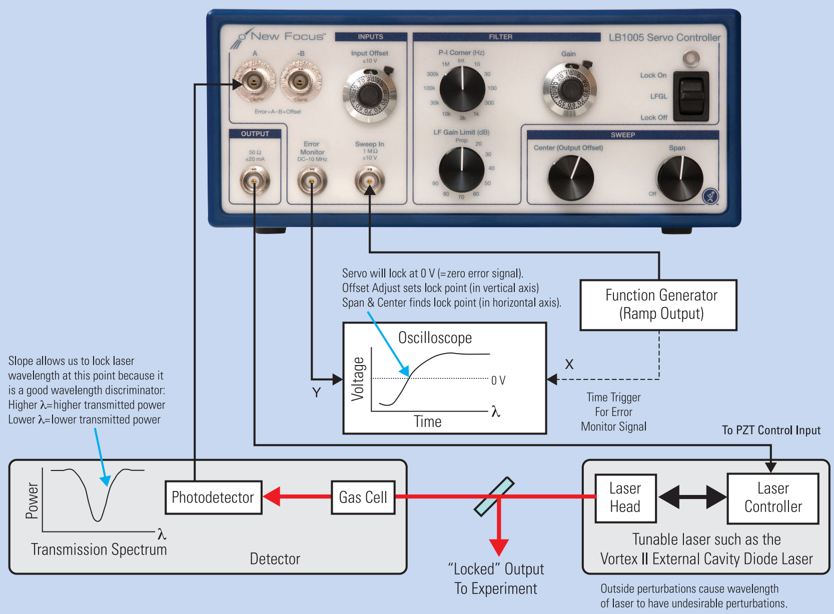
New Focus LB1005 Servo Controller

Specifications	
Input Voltage Noise	<10 nV/√ Hz
Input Impedance	1 MΩ
Input/Output Voltage	±10 V
Bandwidth	>10 MHz
Adjustable Gain	-40 to +40 dB
Adjustable P-I Corner Frequency	10 Hz to 1 MHz
Integrator Hold	TTL Triggered

Wavelength Locking with the LB1005

The wavelength of narrow-linewidth tunable lasers drifts due to floor vibrations, small temperature drifts, and even acoustic noise from people talking in the vicinity of the laser. By using the piezoelectric transducer input to the laser controller, you can shift the laser wavelength so that it always stays fixed on the stable resonance line shape of the sample gas, regardless of possible external disturbances.

To acquire lock, find the locking point by adjusting Sweep Center and Sweep Span (and sometimes Offset Adjust). Upon locating the locking point, the Acquire switch is used to turn on the feedback control. The Sweep Span is then turned OFF, and the Gain can be adjusted to optimize servo control.



Electro-optical Modulators

Aligning modulators is easy with the Model 9071 four axis aligner

Ytterbium Ion Trapping
Model 4855-06
(Blue, 7.37 GHz)

Rubidium Cooling
Model 4851-02
(Visible, 6.8 GHz)

Cesium Cooling
Model 4851-01
(Visible, 9.2 GHz)

Definitions of Characteristics

Absolute Wavelength Accuracy
The maximum difference between the measured wavelength and the displayed wavelength of the laser system.

Amplified Spontaneous Emission (ASE)
The ratio of the optical power at the center of the laser linewidth to the optical power at a given distance, as measured using an optical spectrum analyzer with a set resolution bandwidth.

Coarse-Tuning Resolution
The smallest wavelength change you can make with the coarse-tuning DC motor on the Velocity laser.

Current-Modulation Bandwidth
The highest rate at which the laser diode's current can be changed. This is the 3-dB frequency of the direct-modulation input located at the laser head.

Fine-Frequency Modulation Bandwidth
The highest rate at which the fine-tuning PZT in the laser cavity can modulate the laser frequency. The specified bandwidth is for a 3-dB drop from a low-frequency baseline under small-signal modulation.

Fine-Frequency Tuning Range
The frequency range over which the laser can be piezoelectrically tuned. (If λ is the wavelength of the laser and c is the speed of light, the tuning range expressed in frequency, $\Delta\nu$, and wavelength, $\Delta\lambda$, is related by $\Delta\nu = c \cdot \Delta\lambda / \lambda^2$. Keep in mind that 30 GHz is equivalent to 1 cm^{-1}.)

Integrated Dynamic Range
The ratio of the signal to the source emission, integrated over all wavelengths. This is measured by observing the spectrum of two cascaded fiber-Bragg gratings with a total rejection ratio of >100 dB and a 0.8-nm window, and is a realistic expectation of the dynamic range of your measurement.

Linewidth
The laser's short-term frequency stability. The linewidth varies as a function of integration time. New Focus laser linewidth is specified for 50 ms integration time.

Maximum Coarse-Tuning Speed
The highest guaranteed speed at which the Velocity laser can tune using the coarse-tuning DC motor. The actual maximum coarse-tuning speed for individual systems may vary, but will always be at least this fast.

Minimum Power
The lowest power that the laser will output across its specified tuning range when the current is set to its recommended operating value. Due to changes in diode gain and cavity loss with wavelength, the laser's output power is not constant as it tunes.

Output Power
The typical power that the laser will output across the entire tuning range.

Power Repeatability
The typical difference in power between scans for a given wavelength.

Power Stability
The maximum deviation in power as the laser sits at a specific wavelength over a 1-hour period.

Side-Mode Suppression Ratio
The ratio of the carrier to the nearest side mode.

Tuning Range
The span of wavelengths over which the laser is able to tune.

Tuning Speed
The speed over which the laser can sweep over the entire tuning range.

Typical Maximum Power
The maximum output power you can expect over the laser's tuning range. Due to changes in diode gain and cavity loss with wavelength, the laser's output power is not constant as it tunes.

Wavelength Repeatability
The largest measured deviation that may occur when the laser returns to a given set wavelength. This is a measure of how well the laser returns to a set wavelength over many attempts and when approached from different directions.

Wavelength Resolution
The smallest step the laser can tune.

Wavelength Stability
The maximum amount of drift the laser will exhibit over a specified period of time and temperature variation.

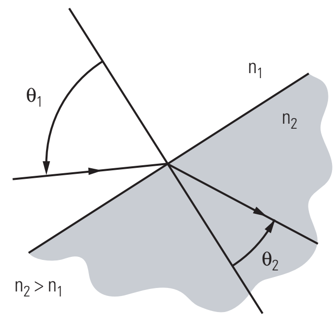
Useful Information

International System of Units (SI) Prefixes

Factor	Name	Symbol
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

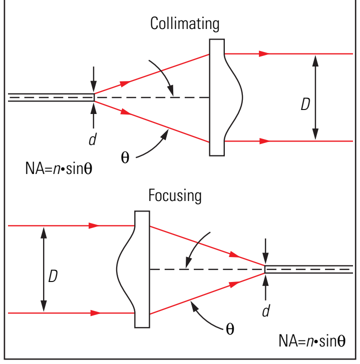
Snell's Law

$n_1 \sin\Theta_1 = n_2 \sin\Theta_2$



Numerical Aperture

$$F/\# = \frac{f}{D} \approx \frac{1}{2 \cdot NA}$$



Wave Quantity Relationship

k=wave vector

ν=frequency

ω=angular frequency $=2\pi\nu$

λ=wavelength

λ_o=wavelength in vacuum

n=refractive index

$$k = \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_o} = \frac{2\pi n\nu}{c} = \frac{n\omega}{c}$$

$$\nu = \frac{c}{\lambda_o} = \frac{c}{n\lambda} = \frac{kc}{2\pi n} = \frac{\omega}{2\pi}$$

$$\lambda = \frac{c}{n\nu} = \frac{\lambda_o}{n} = \frac{2\pi}{k} = \frac{2\pi c}{n\omega}$$

Physical Constants

h =Planck's constant
=6.626×10^{-27} erg•s
=6.626×10^{-34} J•s
=4.5×10^{-15} eV•s

$\hbar$=h/2π=Dirac's constant
=1.054×10^{-27} erg•s
=1.054×10^{-34} J•s

k =Boltzmann's constant
=1.380×10^{-16} erg/K
=8.62×10^{-5} eV/K
=1.380×10^{-23} J/K

kT=25.9 meV at room temperature
=6.7 meV at liquid-nitrogen temperature (77 K)
=0.36 meV at liquid-helium temperature (4.2 K)

c =velocity of light in vacuum
=2.998×10^{8} m/s

e =electron charge
=1.602×10^{-19} coulombs
=4.803×10^{-10} esu

N_o=Avogadro's number
=6.023×10^{23} mol^{-1}

$\alpha_o=h^2/4\pi me^2$=first Bohr radius
=5.292×10^{-11} m

ε_o=permittivity constant
=8.854×10^{-12} F/m

μ_o=permeability constant
=1.257×10^{-6} H/m

m_e=electron rest mass
=9.109×10^{-31} kg

m_p=proton rest mass
=1.672×10^{-27} kg

Energy associated with 1 eV
1 eV=1.602×10^{-12} erg

Wavelength in vacuum associated with 1 eV
1 eV=1.242×10^{-4} cm

Wave number associated with 1 eV
1 eV=8.06×10^{4} cm^{-1}

eV per photon=$1242/\lambda_o$
where λ is in nm

Common Conversions

1 ft=0.3048 m

1 in=2.54 cm

1lb=0.455 kg

Focusing Gaussian Beams

A good way to estimate the best lens to use in your experiment is to choose the focal length of the lens using this formula:

$$f = dD\pi/4\lambda$$

where *f* is the lens focal length, *d* is the beam diameter at the focus, *D* is the $1/e^2$ diameter of the collimated beam, and λ is the wavelength.

A Gaussian beam spreads as follows, where $\omega(x)$

$$\omega^2(x) = \omega_o^2\left[1+\left(\frac{\lambda x}{\omega_o^2}\right)^2\right]$$

is the $1/e^2$ radius and x is the distance from the beam waist where $x=0$.

Optical Density (O.D.), Opacity, and Transmission (%Tx)

O.D.	Opacity	(% Tx)	O.D.	Opacity	(% Tx)	O.D.	Opacity	(% Tx)	O.D.	Opacity	(% Tx)
0	1.0	100	0.8	6.3	16	1.6	40	2.5	2.4	250	0.40
0.1	1.3	80	0.9	8.0	13	1.7	50	2.0	2.5	320	0.32
0.2	1.6	63	1.0	10	10	1.8	63	1.6	2.6	400	0.25
0.3	2.0	50	1.1	13	8.0	1.9	80	1.3	2.7	500	0.20
0.4	2.5	40	1.2	16	6.3	2.0	100	1.0	2.8	630	0.16
0.5	3.2	32	1.3	20	5.0	2.1	130	0.80	2.9	800	0.13
0.6	4.0	25	1.4	25	4.0	2.2	160	0.63	3.0	1000	0.10
0.7	5.0	20	1.5	32	3.2	2.3	200	0.50			

Opacity × Transmission (%) = 100   Optical Density = Log(1/Transmission)   Transmission = $10^{-O.D.}$

www.newport.com/newfocus

New Focus™
A Newport Company

3635 Peterson Way, Santa Clara, CA 95054, USA
PHONE: 1-800-222-6440 1-408-980-4300 FAX: 1-408-919-6083 EMAIL: sales@newfocus.com

	PHONE	EMAIL		PHONE	EMAIL
Belgium	+32-(0)0800-11 257	belgium@newport.com	Irvine, CA, USA	+1-800-222-6440	sales@newport.com
China	+86-10-6267-0065	china@newport.com	Netherlands	+31-(0)30 6592111	netherlands@newport.com
France	+33-(0)1-60-91-68-68	france@newport.com	United Kingdom	+44-1235-432-710	uk@newport.com
Japan	+81-3-3794-5511	spectra-physics@splasers.co.jp	Germany / Austria / Switzerland	+49-(0)6151-708-0	germany@newport.com
Taiwan	+886 -(0)2-2508-4977	sales@newport.com.tw			

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Newport Corporation, Global Headquarters
1791 Deere Avenue, Irvine, CA 92606, USA
PHONE: 1-800-222-6440 1-949-863-3144
EMAIL: sales@newport.com
Complete listings for all global office locations are available online at www.newport.com/contact

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