Ultra-Low Noise and Narrow Linewidth

The monolithic non-planar ring oscillator (NPRO) architecture together with the active noise suppression enable Mephisto to deliver the lowest noise and narrowest linewidth of any commercial laser, making it the source of choice for gravity wave detection, atom cooling and trapping, fiber sensing, long path interferometry and other high-performance applications.

Introduction

Most commercial single frequency lasers used for narrow linewidth applications (Ti:Sapphire lasers, external cavity laser diodes and quantum cascade lasers) provide linewidth in the range 50 kHz to 1 MHz, which is usually adequate for many spectroscopic tasks. Nevertheless, some applications need even narrower linewidth. Since its invention in 1984/5 by Byer, Kane and co-workers at Stanford University [1], the non-planar ring oscillator (NPRO) is still recognized as the lowest noise CW laser architecture. With a cavity based exclusively on a monolithic crystal rather than discrete optical elements, the NPRO can deliver linewidths <1 kHz because of its extremely low phase noise. The Coherent Mephisto's NPRO further lowers the output noise by use of active noise-suppression technology, resulting in the laser industry's quietest laser product. This superior noise and linewidth make the Mephisto the oscillator of choice in leading-edge applications such as the LIGO program aimed at measuring gravity waves by recording length changes as small as 1 part in 10^{22}. In this white paper, we examine how the Mephisto laser delivers its industry-leading performance.

NPRO – Monolithic Stability

One of the keys to low output noise is a stable laser cavity. Typical single-mode lasers incorporate a gain medium and various optics which reside in a resonant cavity formed by two or more mirrors supported by precision mechanical mounts. The NPRO is a completely different type of laser where a single crystal acts as both the gain medium and the laser cavity, which is defined by the crystal facets.

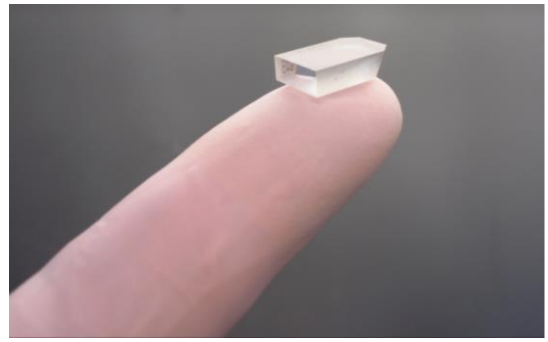

Figure 1 *Size scale of the NPRO crystal which lives in the heart of Coherent's Mephisto family of lasers.*

Just as important, the NPRO acts as a unidirectional traveling wave ring oscillator. In linear laser cavities, the electric field vector of the highest gain mode (and all modes) follows a standing wave pattern along the cavity, causing *hole burning*; the gain is depleted (or undepleted) in a sinusoidal pattern along the cavity. Even though they have lower absolute gain, other longitudinal modes can still oscillate using the gain left undepleted by the strongest mode. Oscillations of undesired modes are eliminated designing the laser to operate as a traveling wave resonator. This type of resonator relies on an *optical diode* to force oscillation on a single direction of propagation. An optical diode is a device whose forward transmission is much higher than its transmission in the reverse direction resulting in a single longitudinal wave propagating along the *forward* direction only. Unlike a standing wave pattern, the traveling wave depletes all the available gain and prevents oscillations of other, undesired modes. One of the clever ideas in the NPRO's design is that the crystal not only acts as the cavity, but also incorporates in a monolithic format all the necessary elements to make an optical diode.

The complete theory of unidirectional NPRO oscillation [2] is beyond this whitepaper. Straightforwardly, the crystal is held in a strong magnetic field, which causes it to act as a Faraday rotator, rotating the polarization of the laser light passing along it by the same amount and direction, independently on the beam direction of propagation (nonreciprocal rotation). In addition, the total internal reflections (TIR) at Facets B and D in

Figure 2 impart a reciprocal rotation to the laser light inside the cavity. The net effect is that in one direction around the cavity the polarization rotations due to the magnetic field and the TIR adds up, while in the opposite direction they cancel each other resulting in two different polarization states for the two modes propagating in opposite directions. The output coupling coating on Facet A can then be designed to slightly favor one polarization, resulting in unidirectional oscillations.

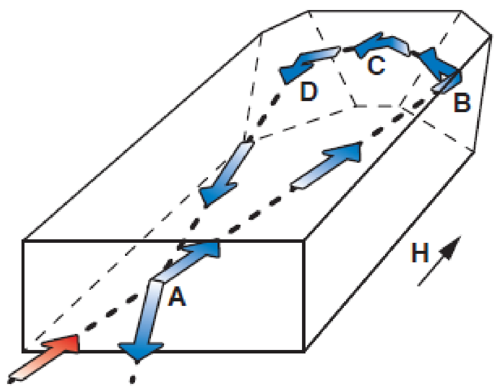

Figure 2 *In a NPRO* the gain crystal forms a monolithic laser cavity, where the facet angles ensure high reflectivity through total internal reflection (TIR). The facets are arranged so that polarization rotation (due to TIR) in combination with an externally applied magnetic field preferentially supports unidirection traveling wave laser operation.

Linewidth and Frequency Tuning

The frequency characteristics of the NPRO – i.e., linewidth – are superior to other laser types. Even today, the latest fiber lasers and external cavity diode lasers cannot reach the same linewidth performance. In the early work at Stanford [3], a linewidth <3 kHz on a short time scale (hundreds of milliseconds) was measured by beating two independent and free-running NPROs. However, this is not the theoretical limit and the latest Mephisto models improve on this value, by providing ~1 kHz specified linewidth for all power versions, again over hundreds of milliseconds.

Of course, a narrow linewidth resonator would be useful only for short term-applications unless drifts can be actively controlled. In Mephisto, two different mechanisms are used to provide fast fine control and slower, coarse control. By extension, this control also provides the ability to tune the absolute frequency of Mephisto.

Fast and fine control is achieved by use of a piezo electric transducer (PZT) element attached to one of the large non-optical facets of the crystal. (i.e., one of the horizontal surfaces in Figure 2.) Compression (strain) of the crystal results in a change of the effective length (or refractive index) that leads to a shift in the frequency of the longitudinal modes. This high-speed loop can be operated up to 100 kHz bandwidth and changes the mode frequency by 1 MHz/V.

Slower but larger frequency variations are addressed by varying the NPRO temperature (temperature tuning). Changes in the temperature of an Nd:YAG monolithic resonator shifts the frequency through two effects: the crystal thermal expansion coefficient and the temperature-dependent change in the refractive index. In addition to these effects, temperature changes can also cause very small shifts in the gain curve of Nd:YAG. Once this is factored in, the net effective change is approximately -3 GHz/K [4]. Figure 3 shows the measured temperature-based frequency control of Mephisto. Mode hops take place when the frequency of the oscillating mode (as determined by the resonator) shifts with respect to the center frequency of the gain-bandwidth by an amount similar to the resonator free spectral range or FSR. The full tuning range of Mephisto is ~30 GHz when the crystal temperature changes by 20°C. This value is lower than the 3 GHz/K value because of mode hops. Figure 4 summarizes the overall tuning characteristics of Mephisto when both temperature and PZT tuning are exercised.

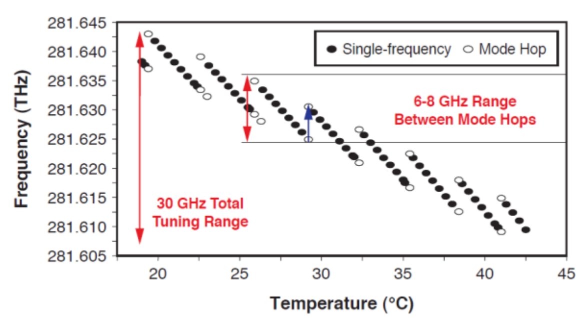

Figure 3 *The Mephisto output frequency as a function of crystal temperature. Mode -hops and regions where two modes can simultaneously oscillate are also indicated.*

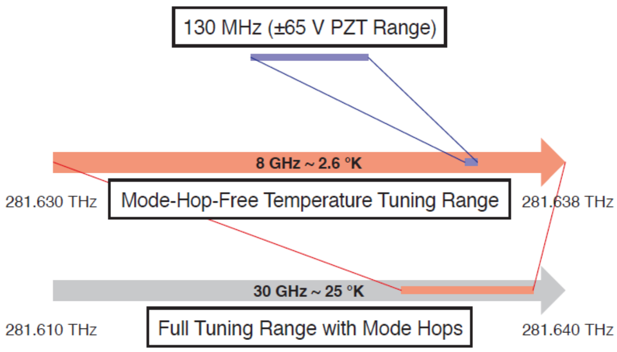

***Figure 4** Mephisto frequency tuning ranges with PZT and temperature controller.*

Phase Noise and Frequency Locking

Phase Noise is the name for the error in the frequency linewidth of the laser. Not surprisingly, the monolithic Mephisto laser resonator yields a frequency noise performance superior to laser resonators made up of individual mirrors that are bound to vibrate or thermally drift with respect to each other. Depending on the intended application this frequency jitter may be expressed in the form of a power spectral density (PSD) statistical distribution in units of Hz/√Hz.

When the Mephisto NPRO's frequency noise is expressed in this way, it follows a 1/f behavior [5]. The frequency noise is about 10^4 Hz/√Hz at 1 Hz and goes down to 1 Hz/√Hz at 10 kHz. Independent tests have previously shown that Mephisto provides the absolute lowest phase noise at all sampling frequencies above 100 Hz. As a result of this unique performance, the Mephisto family of lasers is the optimum choice for applications where the lowest possible frequency noise is required.

The tuning mechanisms can be used to smoothly tune the laser under external control and may also be used to lock the laser output to an external reference for those applications needing an absolute fixed frequency output. This locking also serves to lower the phase noise at low frequencies, compared to simple free-running of the laser. Coherent provides an integrated solution for these applications where the Mephisto output is frequency-doubled and locked to a Doppler-free iodine absorption line. Here the laser head, doubling crystal, iodine (I2) cell and photodetectors are all seamlessly and conveniently incorporated inside a single box that maximized system stability [6]. A typical absolute frequency stability run is shown in Figure 5.

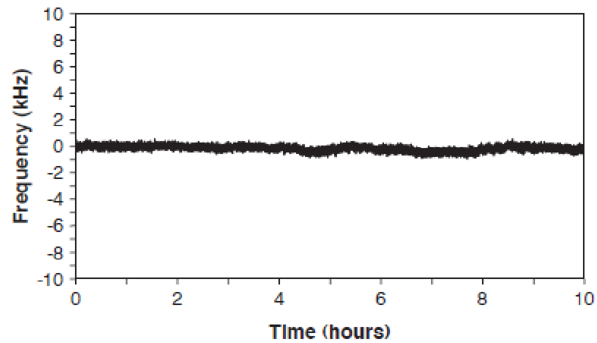

***Figure 5** Ten hour stability run of Coherent's Mephisto (1064 nm) locked with Iodine Frequency Stabilization option.*

Amplitude Noise and Noise Reduction

The Mephisto product line also delivers the lowest amplitude noise. As its name indicates, amplitude noise refers to any minor jitters in the output intensity. Amplitude noise is typically expressed in a form called Relative Intensity Noise which is the noise normalized to the average power level at which it is measured. In a diode-pumped NPRO like Mephisto, the main sources of amplitude noise are relaxation oscillations produced by the residual pump diode noise.

Relaxation oscillations occur in any laser where the upper state lifetime is longer than the cavity damping time, i.e., the time for all the circulating power in the laser to decay (mostly through the output coupler losses) when the laser pump power is turned off. With diode-pumped lasers, when the laser diode pump power changes, even by a small amount, oscillation relaxations will take place producing a peak in the noise spectrum of the NPRO or any other solid-state laser – see Figure 6. In Mephisto this peak is effectively eliminated by use of a feature called Noise Eater. This is a fast feedback loop with the driving signal provided by a photodiode within the laser head and acting on the pump laser diode current. Figure 6 shows how effective this feature is at eliminating pump diode noise across the entire DC to 2 MHz spectral region as well as the relaxation oscillation peak.

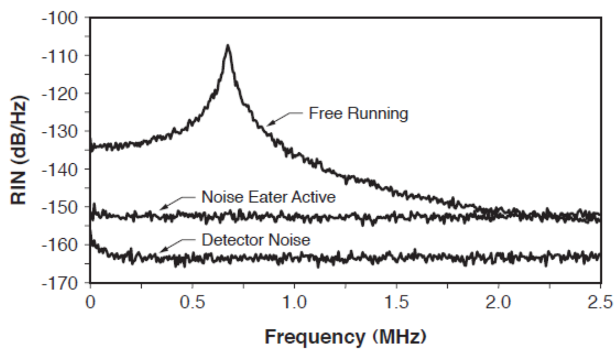

Figure 6 *Mephisto amplitude noise, expressed as RIN (Relative Intensity Noise) between 0 and 2.5 MHz. The Noise Eater circuit is effective in eliminating most of the pump diode current noise as well as the noise peak due to relaxation oscillations.*

Power Scaling and Wavelength Options

In general, as the pump power is scaled up, the NPRO will develop positive thermal lensing with two adverse consequences: the mode matching between pump diode and resonator mode is worsened and the resonator eventually becomes unstable. A detailed study of designing NPROs in the thermal lensing regime [7] shows that when the pump power is increased the thermal lensing will lead to a reduction in the spot size of the mode. Ultimately this will result in a loss of mode matching between pump diode and the resonator fundamental mode, leading to multi-transverse mode oscillation and loss of the main functionality of the NPRO. From these considerations, it is clear that a high power NPRO has a design optimized for the nominal output power rather than for low threshold or high efficiency when used at low power. The NPRO design is scalable to output power as high as 2W, retaining the usual ultra-narrow linewidth, low noise and high frequency stability. If more power is desirable, the best path to achieve tens of watts still retaining the ultra-narrow linewidth is to use a Master Oscillator Power Amplifier (MOPA) approach, available up to 55W of power.

Similarly, although NPROs are most commonly available at the Nd:YAG fundamental wavelength of 1064 nm, specific applications can benefit from different wavelengths. For this reason, Mephisto lasers are available at three different wavelengths: 1064 nm, frequency doubled versions with green (532 nm) output, and also the less common Nd:YAG infrared wavelength of 1319 nm.

Rugged Design

The monolithic resonator design is also more rugged than typical lasers built from discrete components. Not only is the entire cavity enclosed in the bulk of the active medium, but the use of internal reflection from all surfaces except one minimizes the need to use optical coatings. Indeed, the only coated surface is the output facet, but here too, the actual intracavity reflection takes place inside the active medium. This means that the entire laser cavity is contamination-free by design and virtually impervious to damage and aging. This is in stark contrast to most other lasers where designers (and often end-users) have to worry about maintaining optical alignment and laser cavity cleanliness. Furthermore, the small size of the NPRO and pump diodes results in a small head size, making it straightforward to precisely stabilize the operating temperature.

Summary

Mephisto lasers fully exploit the unique potential of the NPRO laser architecture. Their excellent laser beam parameters, unmatched combination of ultra-narrow-linewidth, frequency tuning, high power and extremely low noise make the Mephisto family the laser of choice for sophisticated scientific applications like atom cooling and trapping, optical metrology, quantum optics, gravitational wave studies and other applications requiring extremely narrow linewidth.

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