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Coherence Length and Linewidth of Coherent Lasers

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Introduction

Advance Technical Sales (ATS) often gets questions about the coherence length or the linewidth of a specific Coherent laser system. This Information Bulletin summarizes these parameters for all the laser systems Coherent offers, starting with a short explanation of coherence length, then covers different methods of how to measure the coherence length. A summary of the coherence length for the different lasers will follow and the last section will deal with other laser and experimental parameters in single-frequency applications using Coherent lasers.

Note: Please refer also to Lightworks Volume 94-1 entitled "Visibility Measurement," by Stephen Lee (copy attached).

Coherence Length and Linewidth

The coherence length/time describes distance over which time interval a light wave being emitted by a light source has a fixed phase relationship. For example, an ideal monochromatic wave has only one frequency and the wave never starts or stops – it is a sinusoidal signal going on forever.

No one is perfect and this is also true for a laser. Each laser has a finite linewidth and therefore emits a wavetrain of a specific length or time duration.

One extreme is Coherent's ultrafast laser systems and you know that a certain pulse width is related to a certain bandwidth. We call this relationship "time-bandwidth product." The broader the bandwidth, the shorter the pulse in time and, therefore, the wavetrain in space (a fs pulse has a tiny coherence length). On the other hand, you know that a highly stabilized single-frequency laser like the Model 899-21 has a very narrow linewidth and therefore a long coherence length or "pulse width."

We therefore have the following relationship:

$$\Delta s_{coh} \approx c \bullet \Delta t = \frac{c}{k \bullet \Delta \nu}$$

with ΔS_{coh} the coherence length and Δt the pulse width and $\Delta\nu$ the bandwidth or linewidth.

The exact definition for the coherence length depends a little bit on the customer. For example, customers use a certain level of the fringe visibility to define the coherence length. By doing that, the value for the constant k can vary from about 1 to 3. For further discussions we just take $k = 1$ and keep in mind that customers could use a slightly different definition.

So we will use now the following relationship between coherence length and linewidth:

$$\Delta s_{coh} = \frac{c}{\Delta \nu}$$

How to Measure the Coherence Length or the Linewidth
There are three ways to measure either the coherence length directly, or measure the linewidth and calculate the coherence length with the above-mentioned formula.

1) Michelson Interferometer
A Michelson interferometer was used for the visibility measurements in the Lightworks paper. This is a direct measurement of the coherence length. However, if the coherence length is getting larger the path length difference (PLD), which is the difference in length of the two arms of the interferometer, has to get larger too. Therefore, the Michelson interferometer is only useful for a coherence length up to a couple of meters. The Michelson interferometer is perfect to measure a small coherence length in the 0.5m to 1 mm range.

2) Fabry-Perot Interferometer (FPI)
A FPI is a laser without an active medium or, basically, two mirrors and a mechanical structure to keep these two mirrors a distance L apart. Like in a linear

laser, you get a "mode-structure" with transmission maxima separated by the free spectral range (FSR):

$$FSR = \frac{c}{2L}$$

These transmission maxima can now be used to provide a "frequency standard" to measure the bandwidth of a laser. The issue now is that we deal with the same problems in our frequency standard as we see them in the laser we actually want to measure. These problems are vibrations, or temperature drifts, in the FPI. This limits the use of an FPI to measurements of laser linewidths, which are large compared to the stability of the FPI itself. If this is not the case, you just measure the stability of the complete system laser plus FPI, and you don't know whether it is the laser or the FPI.

3) Atomic Transition

An atomic transition provides an absolute, stable frequency standard. Using a gas cell and looking for the absorption of the laser light in the gas allows laser frequency stability measurements in a similar manner to the FPI set-up. You just don't have to worry about the stability of your reference. The drawback is that most laser lines don't coincide with atomic or molecular transitions.

Note: So, what to do if there is no atomic or molecular transition? The solution is to stabilize laser 1 to an atomic transition. Use a FPI with an optics set covering the wavelength of laser 1 and laser 2 (the one you actually want to test). Stabilize the FPI to laser 1 and use the FPI as a frequency standard for laser 2.

Coherence Length and Linewidth of Coherent Lasers

Here now are typical values for the coherence length and linewidth of our lasers and the method we used to measure these values (this tells you whether we actually measured the linewidth or the coherence length). The effective linewidth of a laser is determined mostly by the acoustic vibrations of the resonator because the vibrations change the cavity length, and therefore the frequency, depending on the observation time a laser will exhibit changes in linewidth or coherent length of the longitudinal mode. Over a short time interval, the laser is only affected by high-frequency, small amplitude vibrations. Temperature changes are too slow and have no affect at all. With increasing time intervals, low-frequency vibrations and temperature drifts broaden the linewidth considerably and limit the coherence length.

So, whenever you talk to a customer about linewidth and coherence length, you should also talk about measurement times and exposure times.

Ion Lasers

Single-line operation

$\Delta\nu$ = 7.5 GHz	ΔS_{coh} = 4 cm	method = #1

Single-frequency operation

$\Delta\nu$ = 10-15 MHz	ΔS_{coh} = 30-20 m	method = #3 with Iodine

The linewidth and coherence length in single-frequency is highly dependent upon the quality of the water cooling. The values mentioned here refer to INNOVA 90, INNOVA 300 and Sabre. The water cooling in the INNOVA 400 or the INNOVA 70 is not as good. Therefore the linewidth out of these lasers might be 2 times bigger.

Single-line operation FRED at 244 nm

$\Delta\nu$ = 7.5 GHz	ΔS_{coh} = 4 cm	method = #1

CW Tunable Lasers

Models 890, 899-01

$\Delta\nu$ <30 GHz	ΔS_{coh} >1 cm	method = #2

Model 899-05

$\Delta\nu$ <10 MHz	ΔS_{coh} >30 m	method = #2

Model 899-21

$\Delta\nu$ <0.5 MHz	ΔS_{coh} >600 m	method = #3

The Model 899-21 demonstrates that, if the effective linewidth of a laser has to be below about 10 MHz, the only way to achieve that is with an active and fast (down to the 0.1 to 1 msec time frame) resonator length stabilization or with a very stable mechanical resonator design (see DPSS).

DPSS

Compass 532

$\Delta\nu$ <2 MHz (<2 μsec) ΔS_{coh} >150 m method = #2

Verdi

$\Delta\nu$ <5 MHz (<50 msec) ΔS_{coh} >60 m method = #2

We do not have linewidth and coherence length measurements specifically for the DPSS systems because method #1 does not work. No one wants to build a Michelson interferometer with a PLD of a couple of 10m (of course we could build one with an PLD of a couple of meters and get a lower limit). Method #3 does not work because we did not yet find an atomic or molecular absorption line at 532 nm. So, we have to live with the limited stability of an FPI.

However, we should put the numbers into a perspective. Let's take Verdi. Here we have a linewidth of 5 MHz for times <50 msec. 50 msec is already a fairly long time corresponding to frequencies vibrational of >20 Hz. Let's assume that the effective linewidth increases by a factor of 10 to 50 MHz, which is very unlikely. This means that the coherence length is still >5m and it is still possible to make holograms from objects about 5m in size!

Lasers used in Holography and Interferometry

So far we talked about the linewidth or coherence length out of a laser. If a customer is doing holography or interferometry, then he is primarily worried about the stability of the fringe pattern. The contrast (or the visibility) is decreasing if the fringe pattern is slowly moving during a holographic exposure and the hologram can become useless. The question to ask now is what is causing a fringe movement? There are just two reasons:

- The frequency stability of the laser
- Changes in the PLD in the holographic or interferometric set-up

By the way, the required coherence length from the laser is only given by the maximum PLD in the holographic set-up.

A typical interferometric set-up (for example, used to write fiber gratings) is shown in Figure 1 (attached). A beam splitter (not shown) devides the laser beam into two beams.

They are overlapped again under the angle θ. They form an interference pattern of equidistant intensity maxima along the line AB with a separation $\Lambda = \lambda/\sin\theta$. If the wavelength λ of the laser is now changed to λ-$\Delta\lambda$ due to a frequency drift of frequency jitter, then the position of the intensity maxima are shifted by $\Delta\Lambda$ along the line AB. This situation is shown in Figure 2 (attached). This movement of the fringes can destroy now the interference measurement or the holographic exposure. Let's assume a customer wants to make a hologram. If the laser wavelength changes at half the total exposure time in such a way to move the fringes by $\Lambda/2$, then he records two equally long exposures with the maxima of one exposure overlapping with the minima of the other exposure. This results in a complete destruction of the hologram.

There is another interesting fact to interferometric set-ups, which is shown in Figure 3 (attached). Here we have a PLD of 10λ due to a mismatch in the length of the two arms of the interferometer. We still have the same wavelength change of $\Delta\lambda/\lambda$ = 1.5% as in Figure 2, but the fringe movement $\Delta\Lambda$ is much bigger now. So, if people don't pay attention to their optical set-up, they can screw up the experiment despite a good enough linewidth from the laser.

But here is now the real issue!
The other source of fringe movement is changes in the PLD of the interferometric set-up.

One possibility for a change in the PLD is the beam splitter of the holographic set-up. If the beam splitter moves by $\lambda/4$, then the PLD changes by $\lambda/2$ and the bright fringes move to the position of the dark fringes. This will completely destroy a holographic image – no matter how stable the laser is – with a mirror movement of only 250 nm! Therefore, customers should make sure that they use very stable mirror mounts for their experiment. Of course, you also have to make sure that your laser does not induce a lot of vibrations into the optical table, for example with the water cooling of an ion laser.

Another possible source of PLD changes is air currents. Turbulent airflow creates changes in the index of refraction and therefore change the optical path length in the two arms of the interferometer.

The conclusion: In most cases, an interferometric or holographic experiment is not working because of the optical set-up. Only in some cases is it the frequency stablility of the laser.

And finally, here are some questions to ask customers with holographic or interferometric applications:

<u>#1 What is the required coherence length?</u>
If the customer does not know the coherence length, ask for the size of the object or the size of the recording material. Also ask whether the optical set-up is symmetrical.

<u>#2 What is the exposure time or measurement time?</u>
Lasers have different coherence lengths depending on the observation time. Let's assume a customer records his hologram in 0.1 sec. In this case, he could, for example, work perfectly with an INNOVA 90 instead of an INNOVA 300.

<u>#3 Is the laser located on the same optical table as the optical set-up?</u>
If the laser is located on another optical table, the bad water-cooling of a Spectra-Physics ion laser is NOT a sales argument.

If you have any questions, please contact me.

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Attachments:
Lightworks Volume 94-1
Figure 1
Figure 2
Figure 3