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2.C Phase Noise in Mode-Locked Laser-Pulse Trains

Many experiments in laser fusion and other areas require synchronized lasers of different pulse durations. Usually this implies generating pulses in separate laser oscillators. The problem then becomes one of synchronizing two or more actively mode-locked laser-pulse trains, each of which is typically affected by its own timing fluctuations or phase noise. In order to overcome this problem, some form of active timing control is desired. Although characterization of noise in mode-locked lasers has been reported in the literature,[1] there has been little direct discussion identifying the possible sources of this phase noise.

The origin of phase noise in typical laboratory lasers is usually not directly related to any fundamental source, but is a result of the mechanics of their construction. Of course, this does not imply a lack of care by those who build lasers, but merely reflects the general sensitivity to perturbations of laser oscillators. Since noise sources are dependent on the details of the individual laser design, general statements about their origin cannot easily be made. Statements about noise based on material properties or common designs, however, are useful, at least for those using similar materials and designs. In this article we discuss phase-noise problems typically encountered in a 100-MHz, cw mode-locked, Nd:YLF laser running at $\lambda = 1.053\ \mu m$. The laser is acousto-optically mode locked and built on an invar table. The cavity has a simple two-mirror stable design producing 80-ps pulses.

Phase-Noise Spectrum

The bulk of the phase noise in solid-state lasers of this type is below 10 KHz.[2] Within this range, the phase-noise spectrum can be divided into two components, which may be described as acoustic (or vibrational) and thermal. The division is appropriate not only because of the different origins and time scales but also because of the techniques used to make the measurements and to the degree in which they affect an experiment. In high-repetition-rate experiments, for example, the slowly varying thermal effects are usually of little concern compared to acoustic perturbations, while in low-repetition-rate laser-fusion experiments the potentially larger magnitude of thermal drifts can become important. Both vibrational and thermal sources can cause changes in the length of the laser cavity and these lead to timing jitter. Thermal effects can also cause phase changes through other mechanisms within active components in the laser.

Thermal Effects

Thermal phase noise or drift occurs on a time scale dependent on the thermal mass of the elements and on the temperature characteristics of the environment. In addition, the thermal response of the laser also depends on the thermal load supplied to the laser rod by the flash lamps and the rf power dissipated in the mode locker. Acousto-optic mode lockers are particularly sensitive to temperature changes since they are resonant devices. Figure 46.24 shows the effect of increasing the input power, or thermal load, to a commercial mode locker with a coolant temperature of 20°C. This device is normally used at 10-W input rf power.

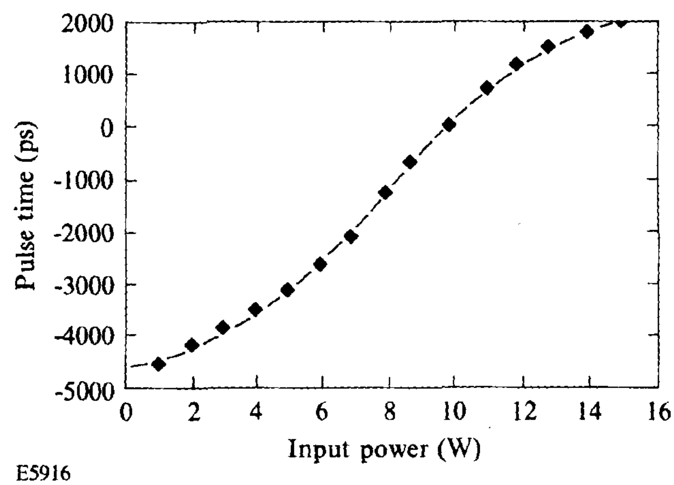

Fig. 46.24
Increasing the input rf power to the mode locker increases its internal temperature, causing a shift in the phase of its acoustic standing wave as it sweeps through resonance. The resonance occurred at about 8-W input rf for a 20°C coolant temperature.

At resonance, the slope is 700 ps/W (rf). Thus for a stability of, say, 10 ps, the input rf power has to be stable to <0.14%, assuming no other sources. Figure 46.25 shows the mode locker's temperature dependence for a constant input power of 10 W. The laser-pulse time versus temperature has a slope of 350 ps/°C. The mode-locker temperature must therefore be stable to < 0.03°C to achieve 10-ps timing stability.

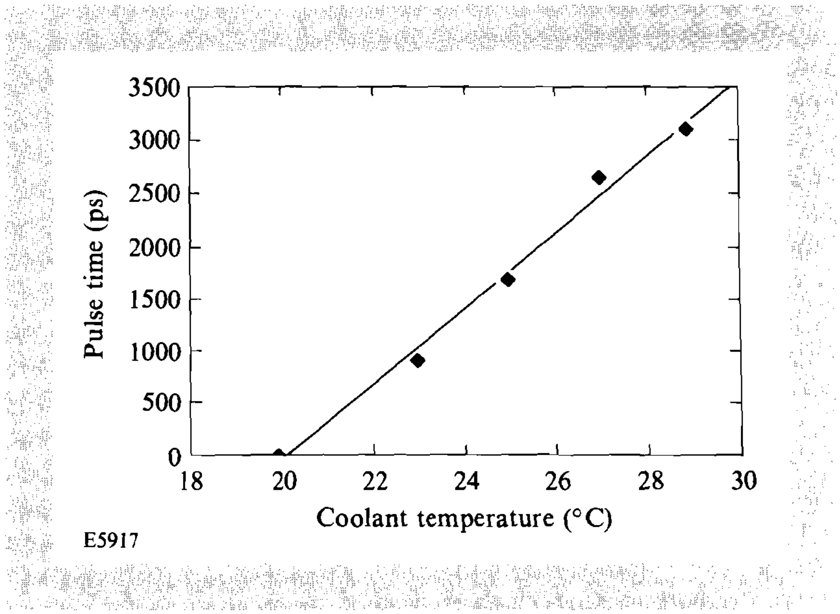

Fig. 46.25
This graph shows the laser-timing shift due to a change in the mode locker's water-bath temperature. Thermal effects in an acousto-optic mode locker can produce huge timing shifts compared to the laser pulse width.

From these results we can see the basis for a technique that uses changes in input rf power to stabilize the mode-locker acoustic-resonance frequency to the rf drive frequency. At 10-W rf, a change in input rf power of 1% is approximately equivalent (thermally) to a coolant temperature change of 0.2°C. Thus small adjustments to the input rf power can be effective in stabilizing the mode locker's temperature and, therefore, its resonance frequency and acoustic wave phase.

It is important to remember that these results depend somewhat on the detailed design of the mode locker. The pulse time versus temperature slope depends on the acoustic Q of the resonant device and on the thermal properties of the optical material used (fused silica in this case). However, results for other devices should be similar.

Acoustic Effects

While thermal effects are on a time scale of seconds to hours, we will consider acoustic or vibrational effects in the frequency range of 1 Hz to 10 KHz or greater. The terms will include any mechanical movement within this bandwidth that induces an optical-path-length change in the laser cavity. Thus, they include effects caused by material index changes as well as those based on physical length changes.

Before continuing with noise sources, the link between cavity length and pulse-train phase shift needs to be shown. Instantaneous measurements of small phase shifts with a phase detector are usually difficult because of amplitude to phase conversion in the detector circuit. However, larger constant shifts measured relative to the rf drive signal are straightforward. Figure 46.26 shows the effect of small changes in the laser cavity length on pulse-train phase shift using a differential micrometer. The data was taken over the course of about 10 min.

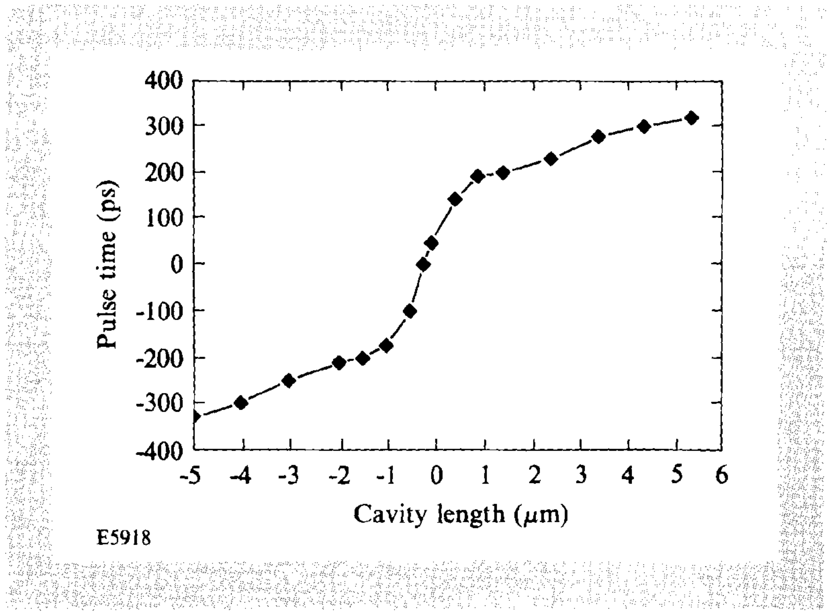

Fig. 46.26
The pulse-train phase is a strong function of laser cavity length. The region of steepest slope is where the mode-locked pulses are shortest. Outside of this region, the laser output power typically becomes less stable.

As is expected for a resonant system, the phase-shift slope is steepest where the cavity length results in a pulse round-trip frequency precisely equal to the rf drive frequency. The slope in this region is 130 ps/μm for a laser running with 80-ps pulses. Again, the results depend on details of the laser. If the laser is operated in the long-pulse regime, the slope in the resonance region is much smaller. For example, for a 750-ps-pulse laser the resulting phase (or timing) shift was found to be negligible over the same range of length adjustment.[3]

This data shows, therefore, that the phase of a short-pulse laser is sensitive to very small fluctuations in cavity length. Of course, this sensitivity is moderated at high frequency by the finite response time of the laser. The exact details of this issue are still under investigation.

Measurement of Cavity Fluctuations

Fluctuations in the laser cavity length due to component movements are easiest to eliminate. The mirrors must be carefully mounted, but this is a requirement of any mode-locked laser. A further consideration is that all sources of vibration must be reduced as much as possible. Even coolant water flow can be a significant source of vibration for continuously pumped systems.

The source of a large fraction of cavity-length fluctuations in our test laser was the result of optical-path-length (OPL) changes in the gain medium. These seem to arise from vibrations induced by turbulent coolant flow over the rod. Measurements of OPL in the rod were made with a Mach-Zehnder interferometer around the laser head. The configuration is shown in Fig. 46.27. In order to include the effect of the vibrational source on the interferometer itself, two measurements were made with the coolant flowing in both cases. In case (a), the interferometer bypasses the rod to establish a baseline fluctuation due only to interferometer instability. In case (b), one arm is repositioned to include the Nd:YLF gain medium. The rod is not optically pumped. Figure 46.28 shows typical results for each case. We see that the OPL fluctuations in the rod are as much as 0.5 μm. This corresponds to a potential 60-ps shift in pulse-train timing or to a 38-mrad phase shift.

Stabilization Methods

Several active feedback techniques can be used to stabilize the phase of the output pulse train. One technique uses the phase of the laser output signal to control cavity length. A problem with this technique is that it adjusts cavity length for any phase change, even one from another source. Thus the cavity length can actually be detuned if the phase noise is a result of other sources.

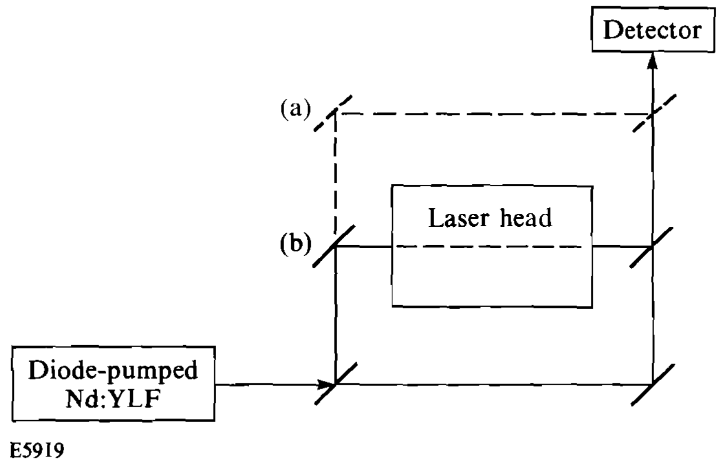

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Fig. 46.27
A Mach-Zehnder interferometer where (a) the interferometer bypasses the laser rod, and (b) one arm passes through the 79-mm × 4-mm rod.

This could produce pulse-width broadening and even unstable laser operation.

In another technique one interferometrically compares and adjusts the laser longitudinal-mode frequencies to an external reference cavity. The advantage of this design is that it isolates cavity-length-induced phase changes from those of other sources, since the interferometer responds to the laser-frequency changes caused by small changes in oscillator OPL. The disadvantage is considerable added complexity and no direct measure of the laser output phase.

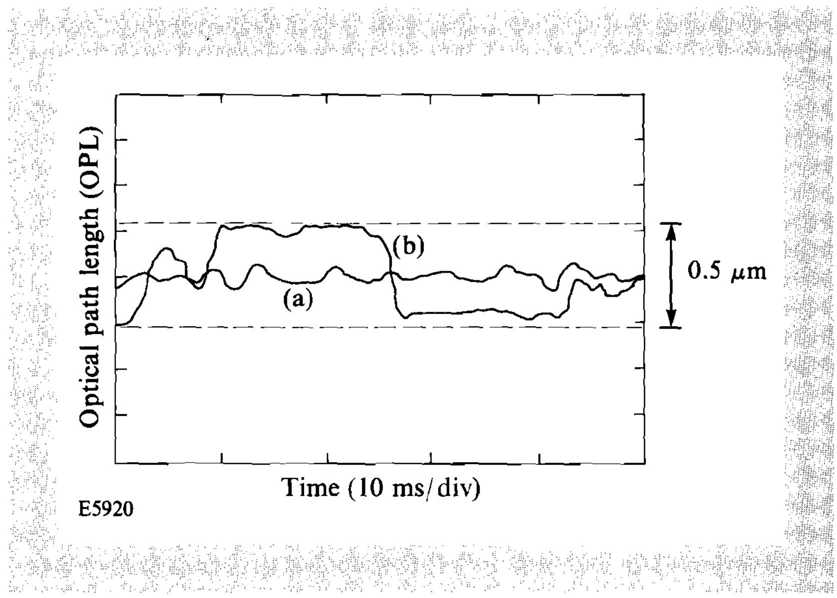

Fig. 46.28
The output from the interferometer shown in Fig. 46.27 where (a) the interferometer bypasses the laser rod, and (b) one arm passes through the rod. The optical-path-length (OPL) fluctuations are due to the turbulent water flow past the rod.

A third technique uses the output pulse-train phase to control the input rf phase to the mode locker.[2] While published results look encouraging, this method essentially works on the symptom of phase noise but does not attempt to correct its source (i.e., no adjustments are made directly to the laser parameters). For example, if the cavity length drifts slightly the laser pulse width may change, which could have an effect similar to a phase change on some experiments. The best solution might be a combination of the second and third techniques to achieve both long-term phase stability and improved overall long-term laser stability. The third technique measures phase directly so that it corrects for phase errors from any source while the second technique acts to maintain optimum cavity length, which is an important source of phase noise and laser instability.

Conclusion

We have found that both thermal and acoustic effects produce significant phase noise in short-pulse mode-locked lasers. We have also shown that severe constraints are placed on both laser cavity length and mode-locker temperature in order to achieve good phase stability of the laser-pulse train. Other effects may also contribute to pulse-train phase instabilities but further work is needed to identify them. By finding the sources of this noise, we hope to eliminate them or improve the effectiveness of active feedback techniques.

ACKNOWLEDGMENT

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