Amplitude noise reduction of 50 dB in colliding-pulse mode-locking dye lasers

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Spurious sidebands observed in the noise spectrum of colliding-pulse mode-locking dye lasers result from coupling of the longitudinal mode beating modulations of the (argon-ion) pump laser with the dye laser. We achieve a 50-dB amplitude noise reduction at the mixing frequencies by inserting a single-frequency étalon in the argon-laser cavity. Furthermore, we find the amplitude noise of the colliding-pulse mode-locking laser to be entirely dominated by the (plasma discharge) noise of the argon laser.

Since its invention in 1981,[1] the colliding-pulse mode-locking (CPM) dye laser has established itself as the workhorse of femtosecond optics and spectroscopy. It gained this status mostly after the incorporation of a four-prism sequence in the CPM cavity to compensate for the group-velocity dispersion.[2,3] The addition of the four-prism sequence eliminated much of the original magic of the CPM laser and made stable generation of optical pulses with less than 100-fsec duration possible on an everyday basis. The CPM laser has been the object of extensive studies to understand the complex pulse-forming and pulse-shaping mechanisms that occur in this laser.[3–5] However, the characterization of the CPM laser noise has not yet received much attention. Although the CPM laser is known for its long-term power stability, its power spectrum shows significant amplitude noise at megahertz frequencies. Von der Linde[6] reported several distinct maxima typically spaced by 1.5 MHz in the power spectrum of a CPM laser and identified them as amplitude noise. The same spurious noise bands were later observed by Chwalek and Dykaar,[7] but in both studies the origin of the modulation was not understood. Only recently have we investigated both the timing jitter and the amplitude noise of the CPM laser and identified the origin of the observed amplitude modulation.[8]

In this Letter, we discuss the spurious modulations found in the power spectrum of CPM lasers and show that insertion of a single-frequency étalon in the cavity of the argon pump laser completely eliminates the spurious modulations and the associated excess amplitude noise. Also, we compare the amplitude noise of the CPM and argon pump laser and find that the plasma discharge noise of the argon laser completely dominates the noise of the CPM laser. Finally, we briefly discuss the significance of the amplitude noise reduction by taking electro-optic sampling of femtosecond electrical pulses as an example.

Power-spectrum techniques for the measurement and characterization of amplitude and phase noise are well-known techniques for the characterization of microwave synthesizers and other microwave devices. However, the enormous wealth of information that can be extracted from power spectra about amplitude noise, timing jitter, and pulse duration fluctuations of mode-locked lasers was only pointed out recently in two excellent papers by von der Linde *et al.*[6,9] Knowledge of the amplitude noise spectrum of lasers is of importance for virtually every optical probing experiment in which the optical probe beam is modulated in proportion to a variable under measurement. Fluctuations in the optical intensity within the detection bandwidth directly translate into fluctuations of the measured variable and therefore degrade the signal-to-noise ratio of the measurement. Since the amplitude noise of most lasers decreases with increasing frequency, the usual remedy to this problem is to translate the detected signal to higher frequencies by chopping techniques. The residual amplitude noise at the chopping frequency then limits the minimum detectable signal for a given acquisition time. Of importance also is the shape of the power spectrum. If the spectrum is strongly structured, as in the present case of the CPM laser, either the chopping frequency has to be kept away from peaks in the noise spectrum or the noise peaks have to be eliminated altogether.

The investigated CPM laser is a six-mirror configuration with an incorporated four-prism sequence for the adjustment of the group-velocity dispersion[2] pumped by ~3 W of the 514-nm line of a Coherent I-200 argon-ion laser. The output coupler is mounted on a translation stage to facilitate variation of the CPM cavity length, originally set to an ~100-MHz

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pulse repetition frequency. The output power of the CPM laser is roughly 25–30 mW into each of the two output beams of the ring laser cavity, with optical pulses of typically 100-fsec duration at a wavelength of 625 nm. The rf amplitude noise of the CPM laser is monitored either with a fast photodiode terminated into 50 Ω for measurements up to ~1 GHz or with a photodiode terminated into a 1-kΩ resistor and a shot-noise-limited buffer amplifier for shot-noise-limited measurements of as much as 5 MHz. In both cases the power spectrum from the diodes is measured with a Hewlett-Packard HP 8566 rf spectrum analyzer with a minimum resolution of 10 Hz. We use the methods described in Refs. 6 and 10 to extract noise figures from the power spectra.

Figure 1 displays a series of noise spectra of the CPM laser recorded with a fast photodiode in a 20-MHz frequency span centered around the fundamental cavity round-trip frequency (~100 MHz) as the cavity length of the CPM laser is varied. At a cavity frequency $f_{\mathrm{CPM}} = 100.23$ MHz, a relatively simple spectrum is observed with only two noise peaks on each side of the fundamental within the displayed frequency span. With decreasing cavity length, these sidebands split into multiple peaks that linearly walk off the original frequency as the cavity length is varied. Eventually, at $f_{\mathrm{CPM}} = 100.48$ MHz, the different peaks recombine, yielding another noise spectrum with only two sidebands on each side of the fundamental within the displayed frequency range. However, the spacing of the sidebands has changed from the situation at $f_{\mathrm{CPM}} = 100.23$ MHz.

We argue that these sidebands originate from the presence of high-frequency modulations of the argon-laser power owing to longitudinal mode beating. These small modulations occur at harmonics of the cavity round-trip frequency of the argon laser, $f_{\mathrm{Ar}} = 76.37$ MHz. Hence, the dye-laser output will also be modulated at the same frequencies, creating sidebands in the power spectrum of the CPM laser. With both the longitudinal mode beating of the argon laser and the CPM spectra having high harmonic content, a large number of different harmonics of the argon-laser and CPM dye-laser output can mix to yield sidebands in the megahertz range. A small number of sidebands, like those at $f_{\mathrm{CPM}} = 100.23$ MHz, can be obtained for a rational ratio of the cavity frequencies f_{Ar} and f_{CPM} of the argon and CPM lasers, $f_{\mathrm{Ar}}/f_{\mathrm{CPM}} = m/n$, with m, n being integers. For example, at $f_{\mathrm{CPM}} = 100.23$ MHz, we find that $m = 16$ and $n = 21$. For a rational ratio, many mixing products of the Kth harmonic of the argon cavity frequency and the Jth harmonic of the CPM cavity frequency yield the same mixing frequencies. For example, the first sideband $f_{\mathrm{mix}} = |Kf_{\mathrm{Ar}} - Jf_{\mathrm{CPM}}| \sim 105$ MHz above the fundamental frequency is obtained with $(K, J) = (4, 2), (17, 14), (25, 18)$, and $(38, 30)$. As the cavity mismatch is changed away from a rational ratio, each mixing product becomes distinct and walks off at a different rate. This rate can be computed for small changes in cavity length[8]: $f_{J,K} = f_0|J(1 - \Delta L/L_0) - Km/n|$, where f_0 is the cavity frequency of the CPM laser at $\Delta L = 0$. The variation of some of the mixing frequencies calculated from this formula are indicated as dotted lines in Fig. 1 and match the observed noise peaks almost perfectly. Each of the smaller sidebands is a separate mixing product, until at $f_{\mathrm{CPM}} = 100.48$ MHz many of these bands overlap again, corresponding to a new rational ratio, $f_{\mathrm{Ar}}/f_{\mathrm{CPM}} = 19/25$, of the argon and CPM cavity frequencies.

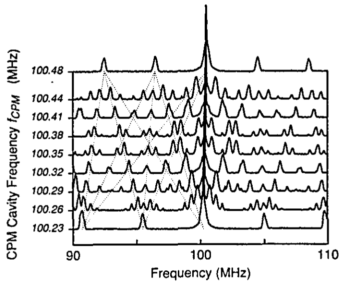

Fig. 1. Evolution of the spurious sidebands in the noise spectrum of the CPM laser as the CPM cavity length is varied. The dotted lines indicate the variation of some of the mixing products with cavity length.

The rf spectrum of the argon laser, although operated in a continuous-wave mode, indeed shows modulations at harmonics of the longitudinal mode spacing (76.37 MHz) with an amplitude of ~0.4%. If this modulation were transfered directly to output fluctuations of the CPM laser, the CPM laser would show modulation sidebands suppressed ~50 dB below the carrier. Actually, we observe the sidebands roughly 60–80 dB below the carrier owing to the nonlinearity of the mixing process. To explain the number of sidebands observed in Fig. 1, the modulations on the argon laser must have power to roughly the 60th harmonic of its cavity frequency. The 8-GHz gain bandwidth of the 514-nm argon line, corresponding to roughly 100 longitudinal modes, is consistent with the high harmonic content of these modulations.

The above interpretation suggests that it is possible to eliminate the spurious modulations by forcing the pump laser into a single longitudinal mode, thereby avoiding longitudinal mode beating and mode competition. In this case, the argon-laser output does not have any modulation at the longitudinal mode beating frequency, therefore $K = 0$ and $f_{J,0} = f_{\mathrm{CPM}}$. The proof of this postulation is illustrated in Fig. 2, which shows a 0–5-MHz span of the power spectrum of the CPM laser with and without a single-frequency êtalon in the argon pump laser cavity. The spectrum is recorded with a shot-noise-limited photodetector–amplifier combination and corresponds to $f_{\mathrm{CPM}} = 100.29$ MHz in Fig. 1. The photodetector is ac coupled so that the dc part of the photocurrent is not shown in proportion. In both cases, the argon-ion-laser pump power and the detector photocurrent are the same. Without the êtalon, sidebands rise roughly 40–50 dB from the background noise with a width of several hundred kilohertz. After placing the single-frequency êtalon in the pump laser cavity, the sidebands disappear completely, and the remaining excess noise of the CPM laser decreases roughly as $1/f$. Although Fig. 2 only displays a 0–5-MHz section of the rf power spectrum, all sidebands between any set of adjacent harmonics of

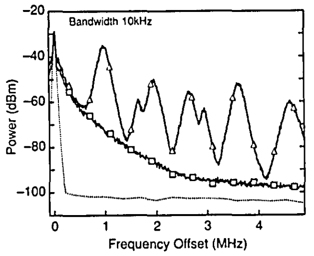

Fig. 2. A 0–5-MHz span of the noise spectrum taken with a shot-noise-limited detector with (squares) and without (triangles) an ètalon in the argon-laser cavity. The system noise with the light beam blocked is plotted as the dotted curve. The photocurrent is ~1 mA.

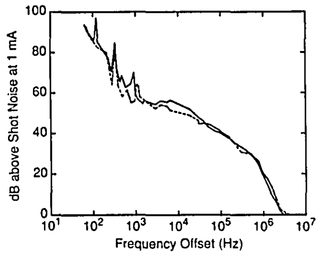

Fig. 3. Amplitude noise of the CPM laser (solid curve) compared with the noise of the argon-ion laser (dashed curve). Both noise spectra are referenced to the detector shot noise at a 1-mA photocurrent.

the cavity frequency disappear after insertion of the ètalon in the pump laser.

A more extended spectrum of the amplitude noise of the CPM laser after incorporation of the ètalon in the pump laser is plotted on a logarithmic scale over a frequency span of 1 Hz to 10 MHz in Fig. 3, referenced to the detector shot noise at a 1-mA photocurrent. For comparison, we also include the measured amplitude noise of the argon laser in the same graph. Both spectra are featureless except for harmonics of the power line frequency below 1 kHz. It is apparent from Fig. 3 that over the entire frequency range from 50 Hz to 3.5 MHz the CPM noise is limited by the (plasma discharge) noise of the argon laser rather than by fluctuations of the dye jets. The amplitude noise reaches the detector shot noise only at ~3.5 MHz.

It is illustrative to estimate the implications of the noise reduction of the CPM laser presented in this Letter for an actual experiment. As an example, we discuss transverse electro-optic sampling of electrical signals on transmission lines using an electro-optic probe tip similar to that of Refs. 11 and 12. We choose this particular example because the noise can be unambiguously characterized in terms of a minimum detectable voltage. However, similar noise reduction can be expected in any optical pump–probe experiment. In the electro-optic sampling experiment, a photoconductive switch generates electrical pulses traveling on coplanar transmission lines 10 μm wide and spaced by 10 μm. We compare conventional chopping at 2 kHz and high-frequency modulation and shot-noise-limited detection at 3.5 MHz. In both experiments, the bias voltage of the photoconductive switch is modulated with a square wave to achieve the desired modulation, although the optical beams could also be chopped, e.g., with an acousto-optic modulator. At 3.5 MHz, the signal from the shot-noise-limited detector is mixed down to 20 kHz with a local oscillator phase locked to the 3.5-MHz pulse modulator so that the signal can be detected with a conventional lock-in amplifier. At a 2-kHz chopping frequency, the measured voltage sensitivity for a 1-mA photocurrent is roughly 80 mV/$\sqrt{\text{Hz}}$. By using a differential detector, the minimum detectable voltage can be improved to 3 mV/$\sqrt{\text{Hz}}$. However, with an ètalon in the pump laser cavity and going to a chopping frequency of 3.5 MHz, we achieve another 60-fold reduction of the detectable voltage to 50 μV/$\sqrt{\text{Hz}}$.

An alternative to placing an ètalon in the pump laser cavity would be to position a narrow-band detection system in one valley of the noise spectrum in Fig. 2. However, this can be difficult because the position as well as the shape of the spurious noise bands changes drastically even for small changes in the cavity length. Such small cavity length changes occur inadvertently when the group-velocity dispersion of the CPM laser is adjusted by changing the beam path through the four-prism sequence.

In conclusion, we have shown that the addition of a single-frequency ètalon in the argon-ion pump laser significantly reduces the amplitude noise of CPM dye lasers by removing spurious sidebands resulting from harmonic mixing of the cavity frequencies of pump and dye laser. Similar effects should happen in any mode-locked laser pumped by a continuous-wave pump source that is not running in a single longitudinal mode. Indeed, we have observed spurious sidebands in a passively mode-locked color-center laser pumped by a continuous-wave Nd:YAG laser.[13] Incorporating a single-frequency ètalon in the respective pump laser cavity will eliminate these sidebands.

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