Characterization of the Complex Noise Transfer Function of a Modelocked Ti:sapphire Laser

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Abstract: We measured the complex amplitude and phase noise transfer functions of a KLM Ti:sapphire laser by modulating the pump laser from 0.1 Hz to 10 MHz. The frequency dependence is in good agreement with theory.

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The recent invention of $f - 2f$ self-referencing modelocked laser clockworks has heralded a new era in precision time and frequency metrology [1, 2]. An essential feature of these new clocks is the inherently low timing jitter of the modelocked lasers which serve as their foundation. There have been many studies of timing jitter (and amplitude noise) in modelocked lasers but only some of the work has focused on the fundamental mechanisms responsible such as beam pointing stability [3], spontaneous emission noise [4] and cavity effects [5].

If we analyze the $f - 2f$ self-referenced modelocked laser as a control system problem, it is essential to characterize the laser’s response to various stimuli so that proper feedback loops can be designed to best accommodate those perturbations. When all sources of “technical noise” from the surrounding environment have been eliminated, one irreducible source of noise remains from pump fluctuations. Recently we characterized the magnitude of a Ti:sapphire laser’s sensitivity to pump fluctuation both in terms of its amplitude and timing-jitter sensitivity [6, 7]. Washburn et al. have also done similar studies in closed-loop fiber lasers [8].

While a record of the magnitudes of the AM and PM sensitivity give a good indication as to the laser’s behavior when pumped by a noisy source, one needs both the magnitude and the phase to design a proper control loop. We report here the measurement of the complex sensitivity of a free-running modelocked Ti:sapphire laser to pump power fluctuations over a frequency range of 0.1 Hz to 10 MHz. We define the amplitude and phase noise transfer functions by

\[ H_{AM}(\omega_m) = \frac{\tilde{m}_{AM}(\omega_m)}{m_p(\omega_m)}, \quad H_{PM}(\omega_m) = \frac{\tilde{\beta}(\omega_m)}{m_p(\omega_m)}. \]

\begin{equation}
\begin{align*}
\tilde{m}_{AM}(\omega_m) & = \text{PUMP MODULATION INDEX} \\
\tilde{m}_{PM}(\omega_m) & = \text{COMPLEX LASER AM INDEX} \\
\tilde{\beta}(\omega_m) & = \text{COMPLEX LASER PM INDEX}
\end{align*}
\end{equation}

and $\omega_m$ is the modulation frequency. The (AM or PM) complex modulation index incorporates both the magnitude and phase of the induced sinusoidal response.

In order to measure complex AM and PM transfer functions it is necessary to modulate the pump laser and coherently detect the amplitude and phase of the demodulated signal. Figure 1 shows the block diagram of the experimental setup. A weak sinusoidal modulation is imparted to the pump with an acousto-optic modulator (AOM). A vector signal analyzer (VSA) is used to drive the AOM and coherently detect the magnitude and phase of the modulations induced on the Ti:sapphire laser. For AM measurements a baseband transimpedance amplifier (AM1) detects the induced amplitude modulation and sends it to the VSA. For PM measurements a phase-locked loop (PLL) maintains a 100 MHz

Fig. 1. Experimental setup for measuring complex AM and PM noise transfer functions of a KLM Ti:sapphire laser.
crystal oscillator in phase quadrature with the 100 MHz detected laser carrier. The phase detector output is then fed to the VSA. In both cases the pump modulation index is recorded at each frequency and all system paths are calibrated for gain and phase.

Measured data and theoretical predictions for $H_{AM}(\omega_m)$ and $H_{PM}(\omega_m)$ are shown in Fig. 2. In the $H_{AM}(\omega_m)$ plot of Fig. 2a, the transfer function is flat below the relaxation oscillation frequency (ROF) as is well known from linearized rate equation analysis. The phase follows the standard form of the single-pole lowpass filter. The behavior of $H_{PM}(\omega_m)$, as seen in Fig. 2b, is considerably more involved. The magnitude also rolls off at -20 dB/decade above the ROF but rolls up again as one tunes down in drive frequency at a rate of +10 dB/decade. The source of this increase in phase sensitivity is predominantly thermal [7]. There is a very low frequency thermal pole but it is not yet evident in our experiment (i.e. $f_{th} < 0.1$ Hz). Owing to $1/f$ noise in the automated measurement configuration, both the magnitude and phase components of $H_{PM}(\omega_m)$ could not be reliably obtained below a modulation frequency of about 5 Hz. Instead, we employed a “spot” measurement technique using an HP3048A phase noise system operating in real-time mode. This permitted magnitude-only data to be acquired from 0.1 Hz-10 MHz, thus filling in the vacancy in the first decade and corroborating the complex data taken with the vector signal analyzer (see Fig. 1). The spot measurement data are shown as yellow triangles in Fig. 2.

In conclusion, we have characterized the sensitivity of a modelocked laser to pump fluctuations over an unprecedented eight order-of-magnitude frequency range. The importance of this work lies in the fact that once the full complex AM and PM transfer functions are known, the free-running performance of the laser can be predicted on the basis of the pump noise spectrum alone. In addition, if the laser is to be used in a closed-loop $f - 2f$ configuration, the complex transfer function of the laser operating as a VCO must be known in order to design optimum control circuits. Finally, since the ultimate noise floor of the pump laser is governed by shot noise, we can use the noise transfer functions to predict the ultimate stability of self-referenced optical clockworks.

References


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