Effect of Self-Phase Modulation on The Signal Quality of Fourier Domain Mode-Locked Lasers

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***Abstract*- In this paper, the impact of self-phase modulation on the noise performance of Fourier Domain Mode-Locked (FDML) lasers is investigated. It is shown that under a relatively high fiber nonlinearity and/or intracavity signal amplitude, an excess amount of noise generation occurs, which can not only lead to poor signal quality, but also operational instability. Hence, particularly for applications requiring relatively high power, careful consideration of the self-phase modulation effect is required.**

I. Introduction

Fourier domain mode-locked (FDML) lasers enable the generation of wideband frequency-swept optical pulses with high repetition rate and low instantaneous bandwidth, which makes them highly useful in detection and imaging applications [1,2]. An FDML laser cavity is mainly composed of three elements, which are the semiconductor optical amplifier (SOA) for round-trip optical gain, the long optical fiber for adjusting the round-trip time for each spectral component, and the optical Fabry-Perot filter for precise filtering of each spectral component at a given instant. Often, the output signal of an FDML laser contains various aberrations that can decrease the utility of the intended output signal for a specific application. The most critical aberration is the frequent formation of sudden dips in signal power, which often leads to a noisy output signal that prevents accurate imaging and detection. Eliminating these power dips (also called *holes* or simply *dips*), has been the aim of recent research on FDML lasers [1, 3-5], which is commonly referred as the *stabilization* process. The dip formation mainly occurs due to the nonlinear SOA dynamics and is strongly aggravated by chromatic fiber dispersion [6,7]. Within the context of stabilization, SOA parameters such as the carrier lifetime (τ) and the linewidth enhancement factor (α) are of significance [1-3], which should be adjusted in the design stage for dip or noise elimination. For the chromatic dispersion that arises in the fiber, a chirped-fiber Bragg grating (CFBG) is usually employed for compensation [1,3]. The self-phase modulation (SPM) effect in the fiber has however not been investigated in the context of dip formation to our knowledge, which is noteworthy owing to the fact that the SPM-caused phase change in the signal cannot be compensated. The SPM effect becomes especially significant when the signal amplitude in the cavity is relatively high. In this study, we saw that despite full dispersion compensation by the CFBG, under high fiber nonlinearity, the power-dips can still form in very large numbers, causing low signal to noise ratio and often an unstable FDML laser operation. Here, we have investigated the SPM effect in terms of Mean Squared Error (MSE) convergence between consecutive round-trips. Our results are in fine agreement with experimental measurements. The results of this study are of importance for both the use of FDML lasers in applications that require high signal power and for future development of FDML lasers in terms of operation bandwidth, round-trip gain factor, and nonlinear intracavity operations, where the effect of SPM can be of high importance for stable operation.

II. Modeling

The occurrence of frequent power-dips on an FDML laser signal envelope is shown in Figure 1. Here, the dips are detected and counted by computing the standard deviation in power, via a moving window of 16 grid-points. It is observed that dip-formation is associated with a minimum power standard deviation of 3mW for an SOA input noise power of 9.05mW [1,3]. In our simulations, the FDML laser operation self-starts through the SOA input noise. The fiber length is set as 444m [1,3].

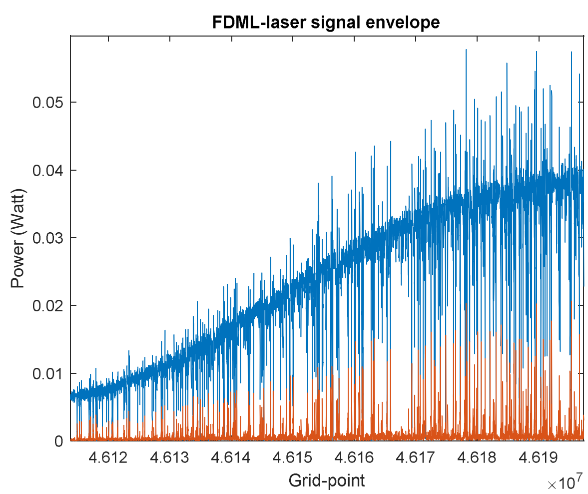

Fig. 1. Power-dips on the signal envelope (blue), which are the main source of noise in the signal, and corresponding standard deviation (orange) computed for dip-detection.

III. Results

Figure 2 illustrates the error convergence with respect to the first 120 roundtrips, under full dispersion compensation and optimized SOA parameters for FDML laser convergence. Hence the MSE is purely due to the SPM. Evidently, the MSE between two consecutive roundtrips converges below a fiber nonlinearity of $2 \times 10^{-2}\mathrm{W}^{-1}\mathrm{m}^{-1}$, above this value, the MSE does not converge to zero, hence the FDML laser operation does not stabilize. The reason for the hindered error convergence can be understood from Figure 3, which shows that the number of holes rises very sharply above the aforementioned fiber nonlinearity.

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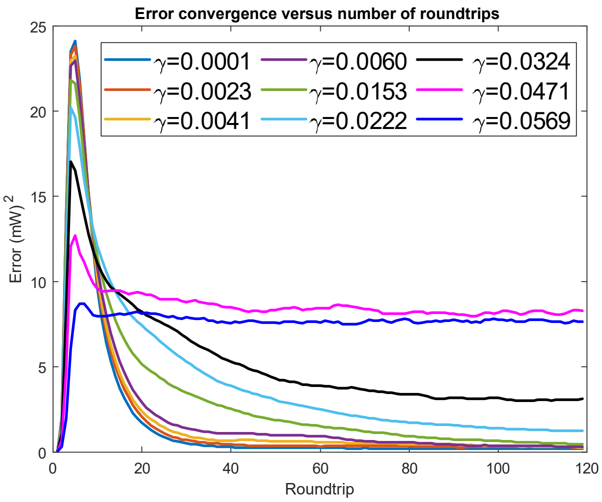

Fig. 2. MSE versus number of roundtrips for various fiber nonlinearities [γ ($W^{-1}m^{-1}$)].

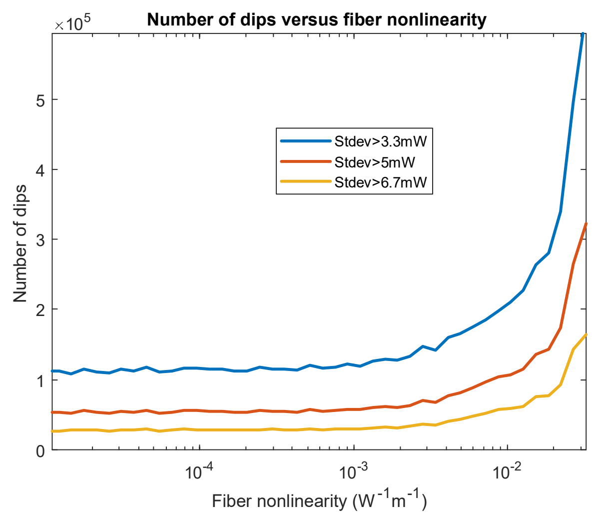

Fig. 3. Number of dips versus fiber nonlinearity [γ ($W^{-1}m^{-1}$)] based on various standard deviations in signal power.

As there are deep/shallow dips that correspond to high/low standard deviations in signal power, Figure 3 represents the change in the number of dips according to their corresponding depth in terms of power standard deviation. Notably, for lower fiber nonlinearities, the number of dips is relatively low, and mostly constant, thereby not preventing the convergence of the FDML laser operation. As the fiber nonlinearity increases, the phase shift in the signal becomes larger, which leads to a greater phase mismatch with the pre-adjusted instantaneous filter response for each spectral component within the SOA gain-bandwidth. Hence, the number of dips sharply increases. Under relatively strong nonlinearity, additional power fluctuations, caused by such drastic increase in the number of dips on the signal pattern, induces the potential for further dip-formation, spiraling the FDML laser operation towards instability. Beyond a certain SPM induced phase-shift, the signal/filter synchronization gets highly distorted and the FDML laser ceases to be operational as a frequency-swept pulse generator.

It should be stated that although the increase in the number of dips is plotted here against fiber nonlinearity (γ), the exact same behavior is also observed against signal power and fiber length. Hence the increase in the number of dips is proportional to the SPM-induced phase shift

$$\psi = \gamma |u_{in}|^2 L$$

γ: *Fiber nonlinearity*, L: *Fiber length*, $|u_{in}|^2$: *Signal power*

Therefore, for applications where relatively high signal power and/or a long fiber length are required, using a fiber with an extremely weak nonlinearity seems to be the only solution concerning the stability and noise performance of FDML lasers.

IV. Summary

For low signal amplitudes and weak fiber nonlinearities, the self-phase modulation effect in the optical fiber has little impact on dip/hole formation and signal quality. When the fiber nonlinearity and/or the intracavity signal power is not so weak, considerable SPM occurs, which causes the formation of excess dips, even under full fiber-dispersion compensation by the CFBG. This not only negatively impacts the stability and the signal-to-noise ratio of an FDML laser but may also cause a totally unstable operation as indicated by the MSE convergence between subsequent roundtrips. Hence, for applications of FDML lasers that require a high intracavity signal power, the SPM effect needs to be considered concerning signal to noise ratio (SNR) and stability of operation.

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