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Characterization of regenerative stabilized actively mode-locked fiber laser incorporating a saturated amplifier in feed-back chain

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ABSTRACT

An actively mode-locked fiber laser with regenerative stabilization established through a feed-back electronic amplifier operated in the saturation regime is reported in this paper. Compared to the regenerative stabilization schemes that employ phase-locked loops (PLL), a saturated amplifier has been used for inhibiting the transmission of amplitude noise through the feed-back chain. Such a laser system has been constructed, studied and characterized as a function of its design variables. Specifically, the electronic phase shift in the feed-back circuit and the RF power applied to the modulator have been varied to study their effect on the mode-locked pulse train. The influence of these parameters on super-mode noise is studied and the optimum values of phase shift and RF power of the recovered carrier at which the noise is found to be a minimum (−48 dB) has been determined. A comparison of systems with and without regenerative mode-locking under controlled conditions reveals that a regenerative system has at-least an order of magnitude better noise performance compared to a system without regeneration.

1. Introduction

Actively mode-locked fiber ring lasers (MLL) are an attractive source for pulses in the pico-seconds range [1] for carrier recovery [2] in optical communication, and photonic analog to digital conversion [3]. However, the pulses generated from such lasers are influenced by a variety of instabilities [4,5]. The source of instabilities primarily consist of pulse breaking due to interaction of the non-linear and dispersive effects in the optical fibre as well as the environmentally-induced changes in cavity length. While the former has been addressed through optical dispersion compensation techniques [6], the latter is typically addressed through electronic compensation techniques aimed towards making the pulse train stable [7].

Regenerative mode-locking has been found to be an efficient and effective method for stabilizing free-space active mode-locked lasers [7]. This scheme was later adapted to fiber lasers in a ring configuration at repetition rates of 1 GHz yielding stable pulses of 640 fs width [8]. Since then, such work has been extended to achieve pulse repetition rates up to 10 GHz at 1550 nm [9] as well as 1064 nm [10]. One of the major problems in the regenerative scheme is the coupling of amplitude noise back into the cavity through the feed-back chain. Several papers have previously analyzed the amplitude noise at each stage of the regenerative feedback [11–14], and it may be mitigated through the use of a phase locked loop (PLL) in the regenerative feedback chain [15]. This scheme has been successfully extended to repetition rates as high as 40 GHz [16,17].

A simpler alternative for addressing the above problem is the use of a saturated amplifier in the feed-back chain. Such a saturated amplifier scheme is widely employed in wireless FM receivers through limiters [18]. This scheme not only decouples the amplitude fluctuations in the regeneration system, but also provides control on the modulation index.

In this paper, we describe the design of a regenerative feed-back system based on the saturation of the electronic amplifier. The characteristics of the mode-locked laser have also been analyzed as a function of the feedback parameters. The effect of detuning parameters on super-mode noise and energy jitter has been evaluated. Finally, we carried out a comparison of a system with and without regeneration to demonstrate the effectiveness of the regenerative scheme.

2. Design of regenerative MLL

The schematic diagram of the active mode-locked laser system, which incorporates the regenerative electronic sub-system is shown in Fig. 1. The ring laser is constructed as a polarization maintaining loop consisting of a gain medium, isolator, output

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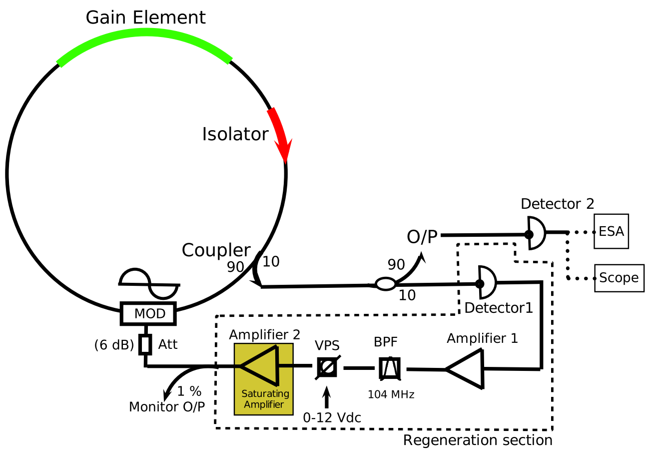

Fig. 1. Schematic diagram of an active MLL with regenerative stabilization. BPF, band pass filter; VPS, voltage-controlled phase shifter; Att, RF attenuator; MOD, amplitude modulator; amplifier 2 is in 1 dB compression.

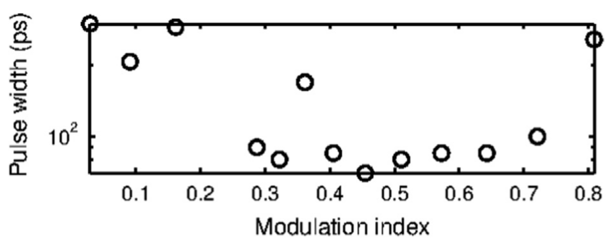

Fig. 2. RF pulse power as a function of modulation index (m) obtained experimentally.

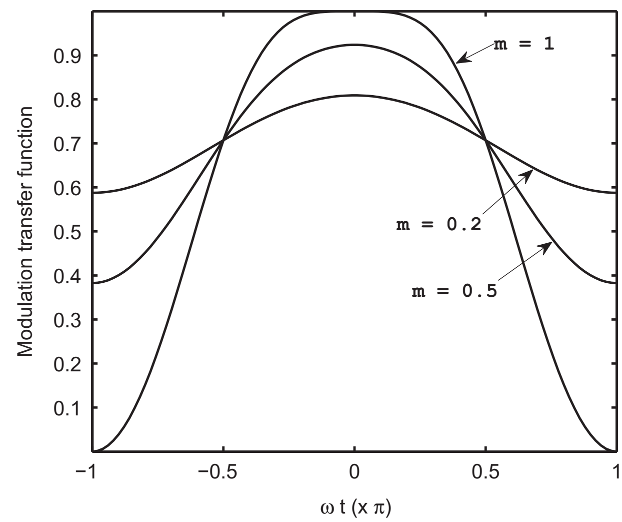

Fig. 3. Modulator transfer function plotted for modulation index (m) of 0.2, 0.5 and 1. The pulse shaping at the center of the modulation window is most effective for modulation index of 0.5.

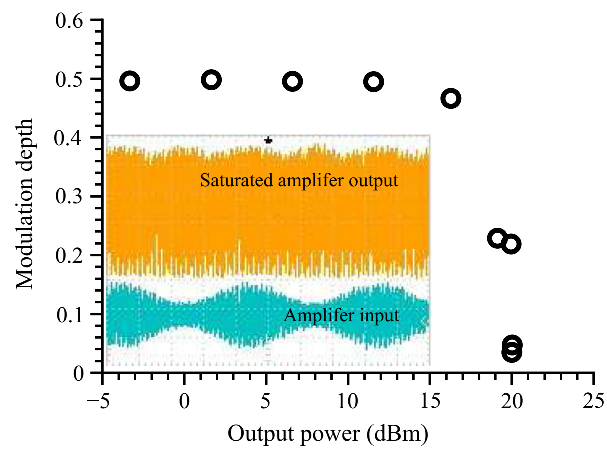

Fig. 4. The modulation depth of an amplitude modulated wave (modulation depth = 0.5) reduces with saturation of the amplifier. The inset shows the time domain profile of the input and output of the amplifier. We can see that a 1 KHz signal amplitude modulated on a carrier gets suppressed, leaving behind just the 100 MHz carrier itself.

coupler and an amplitude modulator (MOD). The modulator is biased at the center of the linear region of its transfer curve. The amplitude modulator is driven at a desired frequency (f_N), which is equal to an integral multiple of the frequency (f_c) corresponding to the round-trip time of the cavity. This frequency (f_N) is extracted from the photo-detected (Detector 1) pulse train using the band-pass filter (BPF) with appropriate amplification (Amplifier 1 and Amplifier 2) in the regenerative chain. The recovered RF carrier at f_N is phase shifted (VPS) to compensate for the phase shift accumulated in the regenerative chain and then fed back to the amplitude modulator (MOD) in the MLL. The regeneration process is seeded by the resonant oscillations of the cavity at f_N.

The RF power fed to the modulator to control the modulation index (modulation depth) has a major influence on the pulse characteristics at the output of the MLL. The effect of modulation index on the width of the pulses generated experimentally by the MLL is shown in Fig. 2. The pulse width is represented in the log scale since it is varying by an order of magnitude. We observe minimum pulse width for a modulation index of 0.45. It may be noted that the data points for modulation index of 0.15 and 0.35 are experimental artifacts. This may be explained by plotting the transfer function of the modulator under sinusoidal RF excitation given by $\cos^2(\pi/4 \cdot (1 - \mathrm{m} \cdot \cos(\omega t)))$ at different modulation indices. The output pulses are broad when the modulation index is much lower than 0.5 since the modulation function is almost flat as shown in Fig. 3. As the modulation index is raised much above 0.5, the modulation function is relatively flat at the center of the modulation window and hence leads to broader pulses. Following the same argument, it may be deduced that the shortest pulses are formed when the modulator is operated at a modulation index of 0.5.

Another factor that affects the MLL output pulse characteristics is the perturbations of the cavity, which can lead to both round trip time fluctuations and amplitude fluctuations. Amplitude fluctuations have both correlated and uncorrelated components [19] with respect to the fluctuations in cavity round trip time. An essential requirement of the regenerative loop is to track only the fluctuations in the cavity round trip time, i.e., the regenerated carrier should be immune to amplitude fluctuations. This requirement was achieved previously by using a phase locked loop [15], but this can also be achieved by operating the final stage of the regenerative amplifier chain in saturation. In order to confirm this hypothesis, a 100 MHz wave is amplitude modulated with a sinusoidal wave of frequency 1 kHz at a modulation depth of 0.5 and fed to the amplifiers in the regenerative chain. The amplifiers are driven to different levels of saturation and the corresponding modulation depth at the amplifier output is measured. As seen from Fig. 4, the modulation depth drastically decreases at higher output powers as the amplifier reaches saturation (above 1 dB compression). This phenomena is used in our scheme to effectively suppress the amplitude noise from coupling back to the laser cavity. Note that the amplifier saturation may change the phase delay in the feed-back chain (which can be countered by appropriately adjusting the phase shifter), but it will not introduce any phase distortion nor phase noise [18]. As the