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Reducing pulse distortion in fast-light pulse propagation through an erbium-doped fiber amplifier using a mutually incoherent background field

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ABSTRACT

It was reported earlier that it is possible to obtain large pulse advancement with minimum pulse distortion in fast-light propagation through an erbium-doped fiber amplifier by placing the pulse on top of a mutually coherent constant background field. Here we show that comparable distortion reduction can be obtained through use of a mutually incoherent background field, a procedure that could be much more readily implemented under many circumstances. We also show that further improvement can be obtained by means of adjusting the pulse power, and for a pulse-power of 100 μW the distortion decreases about 56% from 0.56 with no background while the fractional advancement decreases only about 3% from 0.16.

Recently, several methods for reducing pulse distortion in slow- and fast-light propagation have been reported for applications in telecommunication and information processing [1–8]. Song et al. [1] reported that pulse advancement caused by the large anomalous dispersion appearing between two separated stimulated-Brillouin-scattering (SBS) gain peaks induced less distortion than that of a slightly detuned single gain peak. Stenner et al. [2] achieved reduced distortion in a slow-light system by using an overlapping SBS gain doublet. Compared with a single gain line, the distortion decreased by a factor of 2. Khurgin [3] suggested that the performance of tunable buffers can be improved by using gain flattening. In addition, Minardo et al. [4] applied distortion-management techniques using three equally spaced Lorentzian SBS gain lines. Recently, Shi et al. [5] improved this technique for random pulse trains by optimizing the spacings and relative strengths of the SBS gain lines, and Pant et al. [6] designed optimal gain profiles for broadband SBS slow-light system. Schneider et al. [7] showed zero-broadening in an SBS based slow-light system. Furthermore, Camacho et al. [8] achieved large group delay with low distortion for a pulse tuned between two widely spaced absorption resonances in a rubidium vapor.

In a previous paper [9], we demonstrated that adding a continuous wave background field of appropriate power to the signal pulse can reduce distortion in fast-light propagation through an erbium-doped fiber amplifier (EDFA). This technique, referred to as the pulse-on-background (POB) method, minimizes the pulse distortion by balancing two competing effects.

If a pulse of peak power P_{pulse} is located on a large background field as shown in the inset of Fig. 1, the large background field and the pulse induce a spectral gain hole by coherent population oscillations (CPO) [10,11]. Under these conditions, the spectral wings of the pulse experience more gain than the central frequency component, causing broadening in the frequency domain and pulse compression in the time domain. On the other hand, if a pulse is on a small background field and the pulse duration is comparable with the excited state lifetime of erbium ions, the gain of an EDFA can be saturated by the leading edge of the pulse and then recovered by the strong pump beam. The trailing edge of the pulse on a small background field can experience the recovered gain, broadening the pulse, referred to as *gain recovery* [9,12]. Adjusting these two competing effects by adding a background of appropriate power, pulse distortion can be reduced while maintaining significant pulse advancement.

We have observed that the pulse distortion and advancement depend on the pump power, background-to-pulse power ratio, and pulse width through an erbium-doped fiber amplifier [9]. The EDFA has a CPO response time of 10 ms, which is too slow for applications in telecommunication. However, this long response time facilitates our characterization of the properties of the CPO process that we report here. We believe that the techniques we report here for minimizing pulse distortion can be applied to other CPO systems that display much faster response. In

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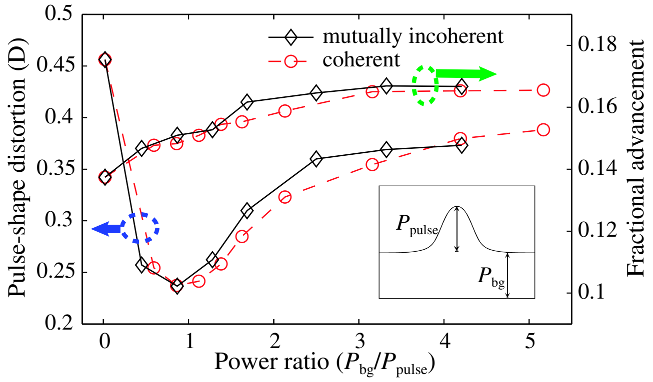

Fig. 1. Experimentally measured pulse-shape distortion (left axis) and fractional advancement (right axis) versus background-to-pulse power ratio for coherent (circles) and mutually incoherent (diamonds) background fields to the pulse. The curves are guides for the eye. Inset: Input pulse waveform. P_{pulse} and P_{bg} represent the power of the pulse and the background field.

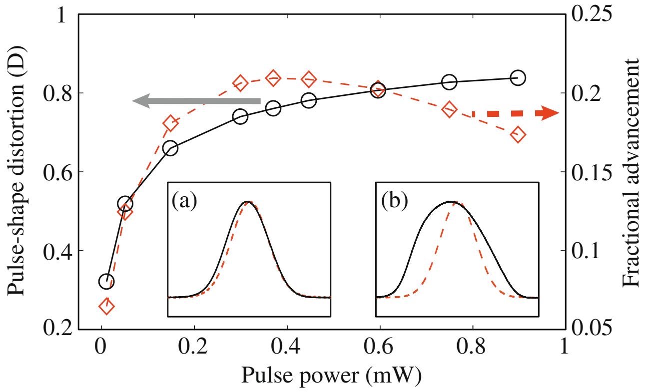

Fig. 2. Experimentally measured pulse-shape distortion (left axis) and fractional advancement (right axis) versus pulse-power, with no background. The curves are guides for the eye. Insets: Experimentally measured input (dashed line) and output (solid line) pulse waveforms are accompanied by (a) pulse-power of 0.01 mW and (b) pulse-power of 0.9 mW.

this paper, we implement the POB method using separate lasers mutually incoherent with each other to generate the pulse and background field. In addition, we investigate the pulse-power dependence of the EDFA system to find the appropriate pulse-power P_{pulse} to obtain the optimum pulse advancement with minimum distortion.

In many systems, it is more convenient to use a separate laser for generating the background field than to use a single laser with an electro-optic modulator (EOM), and in this case the background field and pulse are generally incoherent with each other. When the signals, for instance, are return-to-zero pulses, adding the background field from another laser is more convenient than modifying the signals with an EOM. If we assume that the dipole dephasing time T_2 of the material system is much smaller than the ground state recovery time T_1 and the inverse of the detuning frequency (or modulation frequency) Δ [13], the CPO effect is sensitive only to intensity modulation of the incident laser power. In this case, a background field incoherent to the pulse should have same properties as coherent background field in the POB method. To prove this, we have performed experiments using the methods described in Ref. [9]. A Gaussian pulse of 10-ms duration and 60-μW pulse-power on no background is generated by using an EOM at a wavelength of 1550 nm, another cw laser is used for a background power at 1547 nm, they are combined at a y-junction, and then co-propagate. The pump power P_{pump} was fixed at 17.5 mW, inducing an average inversion level of $(N_{up} - N_{down})/N_{up} = 0.79$, where N_{up} and N_{down} are the number densities of erbium ions in the EDFA.

In Fig. 1, we plot the pulse-shape distortion, the difference between input and output pulse shapes ignoring pulse advancement, as well as the fractional advancement against the background-to-pulse power ratio P_{bg}/P_{pulse} for coherent and incoherent background fields. We take the degree of the pulse-shape distortion to be given by [14]

$$D = \left(\frac{\int_{-\infty}^{+\infty} |P_{out}(t+\Delta t) - P_{ref}(t)|dt}{\int_{-\infty}^{+\infty} P_{ref}(t)dt}\right)^{\frac{1}{2}} - \left(\frac{\int_{-\infty}^{+\infty} |P_{ref}(t+\delta t) - P_{ref}(t)|dt}{\int_{-\infty}^{+\infty} P_{ref}(t)dt}\right)^{\frac{1}{2}} \quad (1)$$

where $P_{out}(t)$ and $P_{ref}(t)$ are the normalized output and reference power envelopes, respectively, and Δt is the time advancement of the pulse. Noise was measured and eliminated from the pulse-shape distortion by subtracting the reference power from the same reference power which is shifted by the temporal resolution of our detection system δt. As shown in Fig. 1, at low (and high) power ratios, the gain recovery (and pulse spectrum broadening) effect induces the pulse-shape distortion, having a minimum value at about power ratio of 1. Note that the POB method operates identically within experimental error in both background cases. Therefore we could find one more degree of freedom for reducing pulse distortion by the POB method in fast-light propagation through an erbium-doped fiber amplifier.

In a previous paper [9], we have reported the pump power and pulse width dependence of the POB method, and the power ratio can be used as a free parameter to minimize the pulse distortion without significantly changing the fractional advancement. In this research, we first investigate the pulse-power dependence of the fractional advancement and pulse-shape distortion using a Gaussian pulse of 10-ms duration on no background to choose

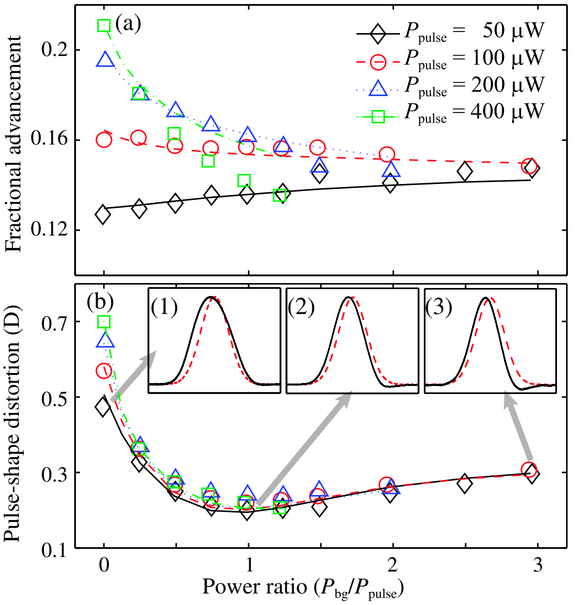

Fig. 3. (a) Experimentally measured (symbols) and theoretically predicted (curves) fractional advancement versus background-to-pulse power ratio for different pulse powers. (b) Experimentally measured (symbols) and theoretically predicted (curves) pulse-shape distortion versus background-to-pulse power ratio. Inset: experimentally measured input (dashed curve) and output (solid curve) pulse waveforms illustrate distortion accompanied by (1) broadening, (2) no pulse-width distortion, and (3) compression.

the optimum pulse-power. In Fig. 2, we plot the pulse-shape distortion and the fractional advancement against the pulse-power. As the pulse-power increases, the pulse-shape distortion also increases but saturates around a pulse-power of 0.3 mW. The fractional advancement has its maximum value at the 0.37-mW pulse-power and then decreases slowly. In inset (a) of Fig. 2, at low pulse-power, the pulse is shifted and broadened by the gain-recovery effect. At high pulse-power as shown in inset (b) of Fig. 2, the output pulse becomes substantially broadened, because the pulse peak is amplified much less than the leading edge of the pulse due to the saturated gain. Therefore, under our experimental condition, the pulse of 0.37-mW pulse-power is expected to have the maximum fractional advancement if we add a background of appropriate power.

Next, we investigate the pulse-power dependence of the POB method, performing experiments and computer simulations using the methods described in Ref. [9]. Using a single laser modulated by an EOM, we generate Gaussian pulses of 10-ms duration with various pulse and background powers. In our previous results [9], we sent a pulse of power of 80 μW through an EDFA, and showed that fractional advancement is independent of the background-to-pulse power ratio. More careful investigation, however, has been performed and shows that pulse advancement depends on pulse-power as shown in Fig. 3a. With increasing power ratio, pulse advancement increases for a pulse-power of 50 μW, is maintained for a power of 100 μW (similar with the power used in our previous results), and decreases for pulse-powers of 200 μW and higher. According to Ref. [15], as the background power increases, the spectral hole induced by CPO becomes deeper at low background power, maintains its line shape at middle power, and becomes broad and shallow at high power. Therefore, the group index related to the line shape of the spectral hole increases at low background power, is conserved at middle power, and decreases at high power. On the other hand, the pulse-shape distortion against the background-to-pulse power ratio does not depend on the pulse-power except at low power ratios as shown in Fig. 3b. The pulse broadening and compression associated with gain recovery and pulse spectrum broadening are shown in inset (1) and (3) of Fig. 3b, respectively. Under our present experimental conditions, the pulse-shape distortion has the minimum value of $\sim$0.2 at power ratio of 1 as shown in inset (2) of Fig. 3b. Finally, we could reduce the pulse-shape distortion from 0.56 to 0.21 (56%) while the fractional advancement maintains its values at about 0.16 (3%) for pulse-power of 100 μW.

In conclusion, we have studied the POB method with a background field mutually incoherent to the pulse and it operates identically with a coherent background case. By demonstrating that a incoherent field can serve as the background, we show a more flexible method for implementing the POB technique of distortion management. We also investigated the pulse-power dependence of the POB method in fast-light propagation through an erbium-doped fiber amplifier. We observed under our conditions that unlike the pulse-shape distortion, pulse advancement depends on pulse-power. Therefore, the EDFA fast-light system can be optimized by selecting the power ratio to minimize distortion and the pulse-power to maximize fractional advancement. We believe the POB technique can be applied to other CPO based fast-light system.

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