# Stacked Optical Precursors from Amplitude and Phase Modulations

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We report the generation of stacked optical precursors from a laser beam whose amplitude or phase is modulated by sequenced on-off step waveforms. Making use of the constructive interference between the precursors produced from different steps, as well as the main field, we generate optical transient pulses having peak powers of eight times the input power with electromagnetically induced transparency in laser-cooled atoms.

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Generating optical pulses with high peak power from a low-power laser is of great interest to many applications, such as optical communication, nonlinear spectroscopy, and optical bioimaging [1,2]. A standard pulse compression scheme takes use of frequency chirping followed by a dispersive compensator [3–5]. Alternatively, pulse compression can also be achieved through a nonlinear medium [6–8]. To convert a continuous-wave laser beam into short pulses with peak power higher than the input, one can implement frequency-phase modulation and the dispersion of a resonant atomic vapor [9], or pass the light through a dispersive modulator [10]. However, the enhancement of the peak power in such a passive system still remains a challenge on the experimental side.

In 1987, Segard *et al.* obtained electromagnetic pulses in microwave regime ($\lambda = 3.5$ mm) with peak intensity of about three times the input whose amplitude is modulated by a series of step pulses and passes through a resonant absorber [11]. The possibility of enhancing the peak power with step phase modulation in optical regime has been discussed [12], but without any experimental demonstration by now. Recently, Jeong and Du [13] revisited this problem and verified theoretically that the coherent transients in Ref. [11] are indeed stacked optical precursors [14,15], and they further proposed an amplitude-modulation scheme to enhance the peak intensity up to seven times the input by making use of electromagnetically induced transparency (EIT) [16]. However, such an enhancement requires very strict parameters, such as high optical depth (>60) and fast switching time (50 ps).

In this Letter, we demonstrate the generation of stacked optical precursors from a laser beam whose amplitude or phase is modulated by sequenced on-off step waveforms. With a low-cost waveform generator (3 ns rise time) for step phase modulation and EIT in laser-cooled atoms with a modest optical depth of 33, we generate optical transient pulses having peak powers of eight times the input power. For the amplitude-modulation case, we provide the experimental demonstration to the recent proposal [13].

The EIT atomic energy level diagram and experimental configuration are shown in Fig. 1. We work with a two-dimensional $^{85}$Rb magneto-optical trap (MOT) with a length $L = 1.5$ cm and a temperature of about 100 $\mu$K. We run the system periodically with a MOT trapping time of 4.5 ms followed by a 0.5-ms measurement window. At the end of the trapping time, all the trapping laser beams are switched off and the atoms are optically pumped to the ground level $|1\rangle$. The 2D quadruple magnetic field has a transverse gradient of 10 G/cm and remains on all the time. A strong coupling laser ($\omega_c$), on resonance with the transition $|2\rangle \rightarrow |3\rangle$, renders the medium transparent for the weak probe laser ($\omega_p$) at the resonance transition $|1\rangle \rightarrow |3\rangle$. The ground-state dephasing rate between $|1\rangle$ and $|2\rangle$ is $\gamma_{12} = 0.01\gamma_{13}$ where $\gamma_{13} = 2\pi \times 3$ MHz is the electric dipole relaxation rate between $|1\rangle$ and $|3\rangle$. Both lasers are operated in the $^{85}$Rb D1-line transitions ($\lambda = 795$ nm) with the same circular polarization ($\sigma^+$). They are aligned collinearly with a small angle (2°) separation so that the coupling laser beam does not enter the detector. The probe laser, whose amplitude or phase is modulated by an electro-optical modulator (EOM, 10–20 GHz, EOspace), passes through the cold atoms, is detected by a photon-multiplier tube (PMT, Hamamatsu, H6780-20, with 0.78 ns rise time) and recorded by a 1 GHz real time digital oscilloscope (Tektronix, TDS684B). The modulation waveforms are generated from a function generator (Tektronix, AFG3252) with a rise time of 3 ns.

Optical precursor response of a single step-amplitude-modulated pulse in the two-level and EIT systems has been well studied in both theory [17–20] and experiment [21–25]. The electric field envelope (complex) of such a step-modulated pulse with an amplitude $E_0$ can be written as $E_{\mathrm{in}}(t) = E_0\Theta(\pm t)$, where $\Theta(t)$ is the Heaviside function, and the $\pm$ signs represent the step-on pulse with a rising edge (+) and the step-off pulse with a falling edge (−). At high optical depth ($\alpha_0 L > 10$), the output precursor transient field can be approximated as [17,19,23,26]

 

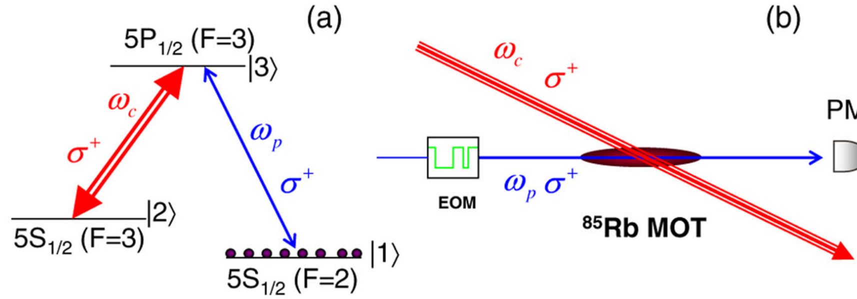


FIG. 1 (color online). System schematics for generating stacked optical precursors. (a) $^{85}$Rb energy level diagram of a three-level EIT system. (b) Experimental setup. In the presence of a strong coupling laser ($\omega_c$) and a weak probe laser beam ($\omega_p$), whose amplitude or phase is modulated by electro-optical modulator (EOM), propagates through a cold $^{85}$Rb atom cloud prepared in a magneto-optical trap (MOT), and is detected by a photon-multiplier tube (PMT).

$$E_{SB\pm}(t) = \pm E_0 J_0[\sqrt{2\alpha_0 L\gamma_{13}(t - L/c)}] \times \Theta(t - L/c)e^{-\gamma_{13}(t-L/c)}, \quad (1)$$

where $\alpha_0$ is the on-resonance absorption coefficient at the probe transition, and $J_0(x)$ is the zeroth-order first-kind Bessel function. If we arrange a series of on and off steps with a time sequence so that the precursor fields produced from all steps at different time interfere constructively, it is possible to generate a transient pulse with higher peak power than that from a single step. For example, as we want to generate a transient pulse at $t_0 + L/c$, the on and off step sequence at the input can be expressed as

$$\mathrm{AM}(t) = \Theta(t - t_0) + \sum_{i=1}^{N-1}(-1)^{i-1}\Theta(t_0 - t - t_i), \quad (2)$$

where $N$ denotes the total number of steps, and $t_i = x_i^2/(2\alpha_0 L\gamma_{13})$. $x_i \simeq (i + 1/4)\pi$ (for $i \geq 1$) is the $i$th zero of the Bessel function $J_1(x)$ that indicates the position of the extreme of $J_0(x)$ in Eq. (1). The peak amplitude of the stacked optical precursor from the amplitude modulation is then obtained at $t_0 + L/c$ as

$$E_{AM} = E_0\left[1 + \sum_{i=1}^{N-1}(-1)^i J_0(x_i)e^{-x_i^2/(2\alpha_0 L)}\right]. \quad (3)$$

However, the above amplitude modulation is not the most efficient scheme to enhance the transient peak because the laser is switched off during some period of dark time. This problem can be solved by applying phase modulation without varying the laser power. A maximum phase modulation with sequenced steps in Eq. (2) can be expressed as

$$\mathrm{PM}(t) = e^{i\pi \mathrm{AM}(t)} = -2\mathrm{AM}(t) + 1, \quad (4)$$

where the second (steady-state) term does not contribute to the transient response. Therefore, such a phase modulation provides a factor of 2 enhancement in the transient field amplitude compared to that with the amplitude modulation. This idea was proposed by Macke and co-workers [11,12], but has not been experimentally demonstrated.

We have one more knob—the main field at the carrier frequency—to further enhance the transient peak power in the EIT system. To do so, we keep the main field in phase with the transient field at time $t_0$ so that they can interfere constructively.

In our realistic experiment, the step modulation has a finite rise (and fall) time of 3 ns. As shown in our early studies [23–25], the finite rise-time effect reduces the precursor transient peak magnitude at high optical depth. On the other hand, Eq. (3) shows that peak of the stacked precursor increases as we increase the optical depth because of the factor $e^{-x_i^2/(2\alpha_0 L)}$. As a result of the competition between these two effects, we find that the peak power of the stacked transient from the amplitude and phase modulation is optimized with the optical depth in the range between 25 and 35, where the transient peak is not sensitive to the change of the optical depth. In the following experiment, we work with cold atoms at optical depth $\alpha_0 L = 33$. From Eq. (3), one can show that the terms with $x_i > \sqrt{2\alpha_0 L}$ contribute little to the total transient field. For $\alpha_0 L = 33$, this is equivalent to $i > 3$.

The experimental observations of stacked optical precursors with sequenced-step amplitude modulation are shown in Fig. 2. Taking into account the EIT and slow light effects on the main field, we set total $N = 4$ on-off steps with $\{t_1, t_2, t_3\} = \{12, 40, 83\}$ ns and $t_0 = 1000$ ns. In the two-level system without the coupling laser present [Fig. 2(a)], the steady-state main field is totally absorbed. Because of the finite rise and fall time, the precursor peak transmission from a single step (e.g., at $t = t_0 - t_3 = 917$ ns) is only about 30%. At $t_0$, we observe a transient pulse with a higher peak transmission of about unity as a result of stacking optical precursors from all four steps. In the EIT system with the coupling laser present [Fig. 2(b)], the peak power reaches about three times that of the input because of the constructive interference between the stacked precursor and the unabsorbed main field. To obtain the theoretical curves, we use the fast-Fourier transform

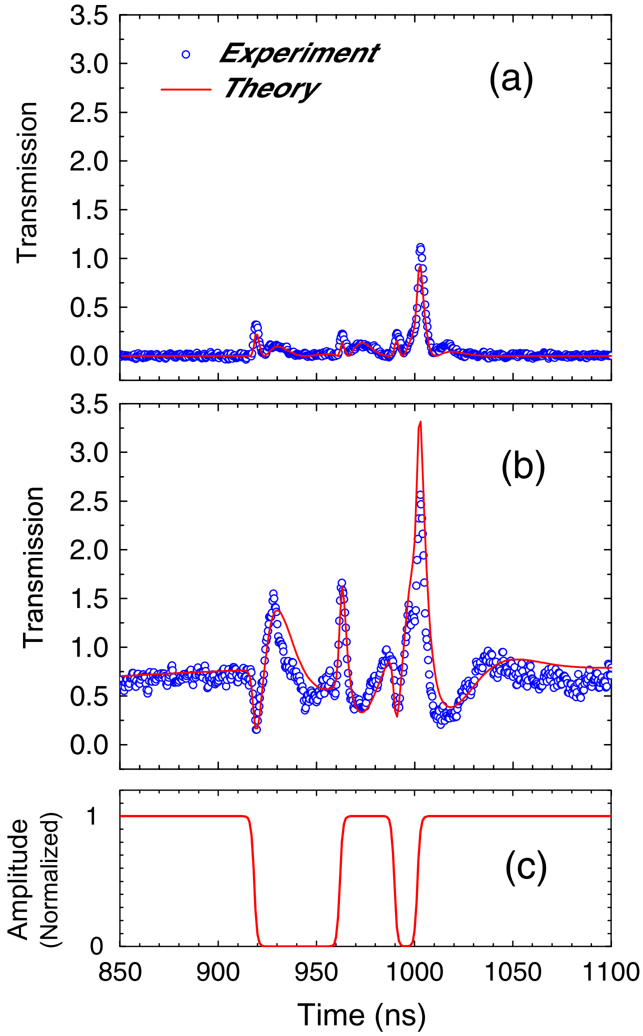


FIG. 2 (color online). Generation of stacked optical precursors from amplitude modulation. Transmission of a weak probe pulse with sequenced on-off step amplitude modulation is shown in (a) the two-level system (coupling Rabi frequency $\Omega_c = 0$) and (b) EIT system ($\Omega_c = 2.5\gamma_{13}$) with optical depth $\alpha_0 L = 33$. Panel (c) is the applied amplitude-modulation waveform.

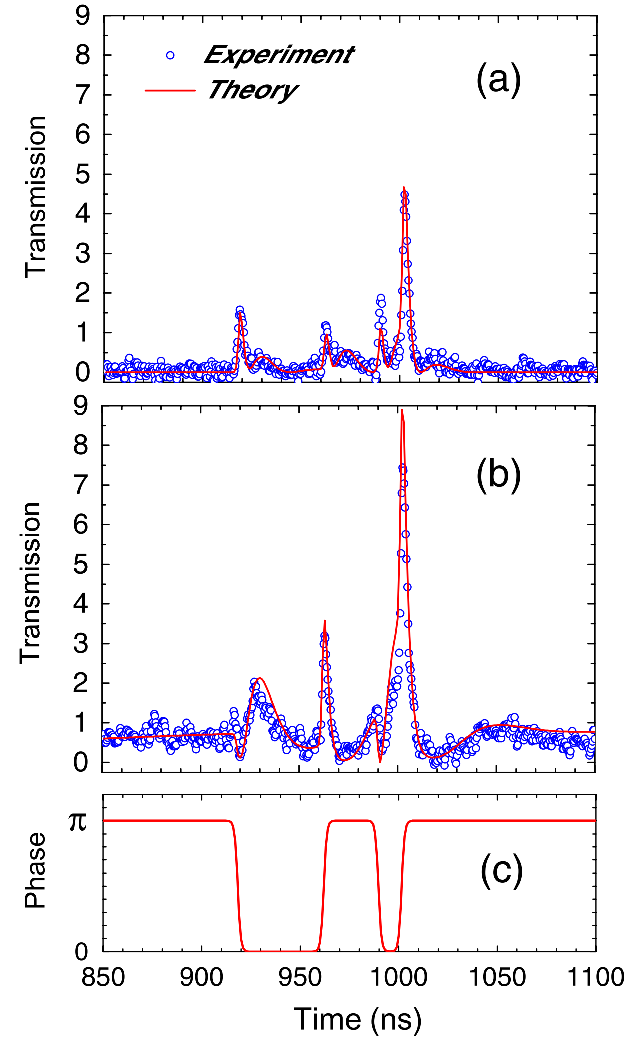


FIG. 3 (color online). Generation of stacked optical precursors from phase modulation. Transmission of a weak probe pulse with sequenced on-off step phase modulation is shown in (a) the two-level system ($\Omega_c = 0$) and (b) EIT system ($\Omega_c = 2.5\gamma_{13}$) with optical depth $\alpha_0 L = 33$. Panel (c) is the applied phase-modulation waveform.

and simulate the realistic step function with a finite rise (fall) time of $\Delta t = 3$ ns with a hyperbolic tangent function $\Theta(t) \rightarrow [1 + \tanh(2t/\Delta t - 1)]/2$. They agree well with the experimental data.

Then we replace the amplitude modulator with a phase modulator. The modulation waveform remains the same. The experimental results from the two-level and EIT systems are shown in Fig. 3. Compared to that with amplitude modulation shown in Fig. 2, the enhancement on the transient peaks is dramatic, while, as expected, the shapes are nearly identical. In the two-level system, the transient peak transmission at $t_0$ increases from 1.2 to 4.5, consistent with the prediction from Eq. (4). In the EIT system, the transient peak goes up to about eight times the input.

The transient pulse peak power can be enhanced more if we have a faster waveform generator. Figure 4 shows the peak transmission from phase modulation as a function of the rise time at two different optical depths in the EIT system. Obviously, at our current configuration with the finite rise time of 3 ns, the peak transmission is not sensitive to the optical depth as we have discussed previously. As the rise time reduces to $<0.1$ ns, the peak transmissions go up to about 15 for $\alpha_0 L = 33$, and 18 for $\alpha_0 L = 66$.

In summary, we have generated stacked optical precursors from the two-level and EIT cold atom systems ($\alpha_0 L = 33$), with the input probe field amplitude or phase modulated by predesigned, sequenced, on-off step waveforms. In the amplitude-modulation case, we provide the first experimental demonstration for the recent proposal by Jeong and

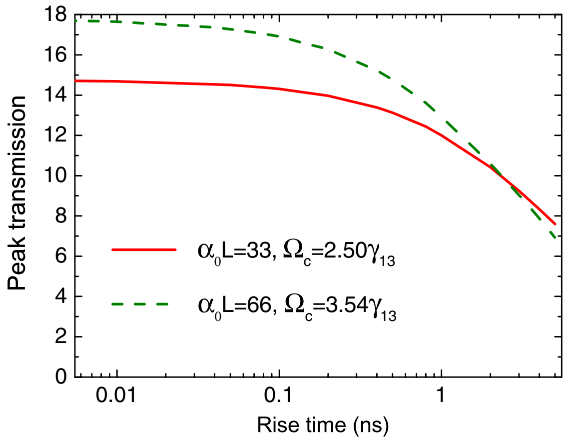


FIG. 4 (color online). The normalized transient peak intensity as a function of the finite rise time in the EIT system from phase modulation. For $\alpha_0 L = 66$, the coupling Rabi frequency ($\Omega_c$) is adjusted to have the same main field transmission (80%) as that at $\alpha_0 L = 33$.

Du [13]. With the phase modulation we obtain a transient pulse with a peak power of eight times that of the input, as a result of constructive interference between the stacked precursor and main field. A higher peak transmission of about 15 can be achieved if the rise (and fall) time can be shortened to <0.1 ns. We note that there is a difference between this technique and the well-known dispersion-based pulse compression scheme [3,4,9,10]: the optical precursors come from the spectral components that are far away from the atomic resonance and thus experience very little, but still necessary dispersion. We would also like to emphasize that we are working with a linear passive absorptive system without any gain. The result suggests that our atomic system may work as an efficient differential phase-shift keying demodulator for optical communication.

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