Control of Stimulated Raman Scattering in the Strongly Nonlinear and Kinetic Regime Using Spike Trains of Uneven Duration and Delay: STUD Pulses

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Stimulated Raman scattering (SRS) in its strongly nonlinear, kinetic regime is controlled by a technique of deterministic, strong temporal modulation and spatial scrambling of laser speckle patterns, called Spike Trains of Uneven Duration and Delay (STUD pulses) [B. Afeyan and S. Hüller, Phys. Rev. Lett. (submitted)]. Kinetic simulations show that use of STUD pulses may decrease SRS reflectivity by more than an order of magnitude over random-phase-plate (RPP) or induced-spatial-incoherence (ISI) beams of the same average intensity and comparable bandwidth.

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Laser-plasma instabilities (LPI) pose a risk to the realization of laser-driven inertial confinement fusion (ICF) ignition [1]. The present approach is to use continuous, ns-time-scale illumination of a target with high-intensity laser beams. However, because of LPI, this may prove to be less than ideal when compared with a novel technique invented by Afeyan [2] employing intermittent, scintillating, space-time illumination which may significantly reduce the levels of nonlinear optical processes. The efficacy of this technique, which employs Spike Trains of Uneven Duration and Delay (STUD pulses), has been demonstrated in the fluid regime of instability evolution from low to moderate gains per speckle, where the linear growth is halted by the use of STUD pulses and any saturation is from pump depletion [3][4]. This Letter focuses on the application of STUD pulses to Stimulated Raman Scattering (SRS) in settings where kinetic nonlinearity dominates the evolution of driven electron plasma waves (EPW) and where multi-laser-speckle, cooperative behavior can proceed through the exchange of hot electrons and SRS scattered light among laser speckles [5][7]. We find from our initial study that more than order-of-magnitude reduction in SRS reflectivity can be achieved. The key is to keep SRS growth below the level where secondary, nonlinear processes causing cooperative behavior among hot spots can occur, thus disallowing the self-organized state.

SRS is the resonant, three-wave coupling of a light wave into scattered light and electron plasma waves. It is an LPI process occurring in large amounts in indirect-drive ICF experiments with potentially deleterious effects, including scattering of laser energy out of the hohlraum, redirection of energy within the hohlraum, and generation of hot electrons that may contribute to capsule preheat. At the National Ignition Facility (NIF), experiments show ~50% inner-cone beam energy loss to SRS [1]. Laser facilities such as OMEGA and the NIF employ beam smoothing, whereby random phase plates (RPP) break the laser beams into “speckles” to effect a quasi-uniform (on the large scale) intensity profile across the beam, though introducing into the beam small-scale, high-intensity variations or “speckles.” In vacuum, speckles have characteristic size $8f^2\lambda_0$ (longitudinally) by $f\lambda_0$ (transversely), where $f$ is the optical focal parameter and $\lambda_0$ is the laser wavelength. The scaling of SRS reflectivity $R_{SRS}$ with laser intensity $I$ in a solitary speckle in plasma has been measured [8] and found in the electron trapping regime $k\lambda_{De} \gtrsim 0.3$ ($k$ is the EPW wave number and $\lambda_{De} = \sqrt{k_BT_e/4\pi n_e e^2}$ is the Debye length for plasma of electron density $n_e$ and temperature $T_e$) to behave nonlinearly, increasing sharply at a threshold intensity $I_{th}$ and saturating for $I > I_{th}$. The physics in this regime is governed by the growth of large-amplitude EPW that trap “resonant” electrons with speeds along the wave propagation direction matching the wave’s phase speed; this reduces local Landau damping [9], enhances instability growth, and lowers the EPW frequency [10]. At high intensity, trapping introduces variation in EPW phase velocity across the speckle and causes wave phase fronts to bend [11][14]. As EPW grow to large amplitude, secondary, nonlinear processes have been proposed to break the phase fronts into small-transverse-scale filaments [14][10] that further contribute to nonlinear saturation. An effect of saturation, observed in simulations [5], is the generation of hot electrons and back- and side-scattered light waves that propagate obliquely out of hot spots and enhance SRS growth in neighboring speckles through larger SRS seed levels and reduced EPW Landau damping. At high gain in two spatial dimensions (2D), this coupling enables networks of speckles to self-organize [5] and exhibit emergent behavior where reflectivity exceeds that of the sum of contributions from individual, non-interacting speckles. The nonlinear nature of SRS in this regime is robust, with a threshold at modest laser intensity, $\gtrsim 10^{14} \text{W/cm}^2$ for NIF laser conditions where $k\lambda_{De} \approx 0.3$ and the highest levels of backscatter are found [17].

Our intent here is to show that the use of STUD pulses [2], effective for controlling LPI over long time scales in the fluid regime of instability evolution [2][4],
may also inhibit EPW growth in the highly nonlinear, kinetic regime. STUD pulses deliver laser power in a sequence of pulses or spikes on the instability growth or hot spot crossing time scale (sub-ps, typically, for SRS) with randomized laser speckle patterns in between one or more successive spikes. By introducing on-off sequences of pulses and by spatially scrambling locations of hot spots, reinforcing processes within a hot spot and the interconnectivity between hot spots that leads to large instability growth are disrupted. STUD pulses reduce degrees of freedom that can be optimized. These include the ratios \( L_{\text{HS}} : L_{\text{INT}} : L_{\text{spike}} \), where the interaction length is \( L_{\text{INT}} = 4L_0\frac{\alpha^2I_{14} + (\nu_2/\omega_2)^2}{2} \). Here, the density scale length is \( L_n = |\nabla \log n_e|^{-1} \), \( I_{14} \) is intensity in \( 10^{14} \text{ W/cm}^2 \), \( \nu_2 \) and \( \omega_2 \) are the local Landau damping rate and frequency of the EPW, respectively, \( \alpha^2 = 1.42\lambda_{\text{scram}}^2L_0^{100}\mu \text{m} |V_1/V_2| (n_e/n_{e\text{cr}})^{-1} \), and \( V_1/V_2 \) is the ratio of group velocities of scattered SRS light to the EPW. Spike length \( L_{\text{spike}} \) is the distance traveled by scattered light during the ‘on’ time \( \tau_{\text{spike}} \) and \( L_{\text{HS}} \sim 4f^2\lambda_0 = 90 \mu \text{m} \) is the characteristic size of a hot spot in our plasma. Other degrees of freedom are duty cycle (the ratio of \( \tau_{\text{spike}} \) to on-off time), the spatial scrambling rate \( \times n_{\text{scram}} \) (how many identical spikes before the RPP pattern changes) and the “jitter” (random variation of each \( \tau_{\text{spike}} \)). All calculations in this Letter used 0% jitter. Hence, “5000×1, 1:1:1/2” indicates a STUD pulse sequence with 50% duty cycle, 0% jitter, and a spike duration half as long as a hot spot crossing time in plasma where the time to cross \( L_{\text{INT}} \) for the three-wave process is comparable to that of crossing the hot spot. Most of the results we present are for cases 5000×1, 1:1:1/2 and 1:1:1 in strong to very strong nonlinear kinetic regimes (SRS gains of 6–11 at the average intensity). Note that configurations where ‘on’ time is much greater than ‘off’ time, e.g., 8000×1 or 9500×1, resemble the ISI model of beam smoothing [18] at the same bandwidth.

To understand better the behavior of STUD pulses in the trapping regime, we run VPIC particle-in-cell simulations [19] of a 2D plasma of size 500 × 80 \( \mu \text{m} \) in \((x,z)\), with a laser beam polarized along \( y \) launched at \( x = 0 \) as described in Ref. [6]. The laser has wavelength \( \lambda_0 = 0.351 \mu \text{m} \) and an RPP speckle pattern for \( f \)/8 speckles is used, approximating a NIF inner-cone beam in hohlraum plasma. The density has a gradient along \( x \) with \( n_e = 0.12n_{e\text{cr}} \) at the center, changing from \( \pm 0.03n_{e\text{cr}} \) to \( \pm 0.03n_{e\text{cr}} \) across the box, comparable to the \( L_n \sim \text{mm} \) encountered in NIF ignition hohlraums in regions of high SRS backscatter [17]. Taking \( \nu_2 = \nu_{2\text{Max}} \), as for Maxwellian plasma, in the \( k\lambda_{\text{De}} \approx 0.3 \) regime yields \( L_{\text{INT}} \sim 95-99 \mu \text{m} \) for the range of intensities simulated. We use 36864 × 4096 cells (\( \Delta x = 1.2\lambda_{\text{De}} \) and \( \Delta z = 1.7\lambda_{\text{De}} \)) and 256–512 electron macroparticles/cell; ions are stationary. The electrons have \( T_e = 2.6 \text{ keV} \) (\( k\lambda_{\text{De}} = 0.3 \)). The STUD pulse speckle patterns are generated from pre-computed RPP phases for a wide beam, sampling 80–\( \mu \text{m} \), non-overlapping segments for each STUD pulse. Each simulation employs the same sequence of speckle patterns to within an overall intensity modulation, allowing variation of intensity, duty cycle, and modulation period. (Statistical variation was assessed by altering the sequences of STUD pulses; \( \sim 10\% \) relative \( R_{\text{SRS}} \) variation was found in a range of cases considered.) The simulation boundaries absorb electromagnetic waves and re-ject electrons as Maxwellian at initial temperature \( T_e \). The simulations were run until apparent “steady-state” in time-averaged \( R_{\text{SRS}} \), 10–20 ps.

Fig. 1 shows a comparison of three simulations: (a) (top row) is for an RPP beam with \( \langle I \rangle = 5 \times 10^{14} \text{ W/cm}^2 \) (\( G = 11 \)); (c) (bottom) is for a STUD pulse beam of time-averaged laser intensity \( \langle I \rangle = 3.2 \times 10^{14} \text{ W/cm}^2 \) (\( G = 7.5 \)). Linear SRS gains \( G \) are computed from \( G = 4\pi (\gamma_0/\omega_0)^2 |2\pi L_0/\lambda_0| g(n/n_{e\text{cr}})^{-1} (1 - \nu_1\nu_2/\gamma_0^2) \), where \( (\gamma_0/\omega_0) = 0.0043\sqrt{T_{14}/\lambda_0^2} \), \( \nu_1 \) is the damping rate of the daughter light wave, and \( g(n) = \sqrt{1 - 2\sqrt{n}/(1/\sqrt{n}) - 1} \). Accounting for backscatter loss, (a) and (c) have comparable net time-averaged power at the left boundary, though (c) has only 64% of the incident time-averaged laser power. Case (b) (center) is for a STUD pulse beam at the same time-averaged incident laser intensity as (a): \( \langle I \rangle = 5 \times 10^{14} \text{ W/cm}^2 \)
$10^{14}$ W/cm² ($G = 11$). The leftmost panels show $E_y$ (or the vacuum speckle pattern for the RPP case). The rightmost panels are instantaneous backscattered Poynting flux max $(-E_y B_z, 0)$. Case (a) evinces continual bursts of self-organized backscatter with peak $R_{SRS} > 1$. In (c), no self-organization is seen in backscattered light or longitudinal electric field. Case (b) is intermediate, showing quiescent periods of low backscatter punctuated by occasional episodes of partial self-organization when large-amplitude speckles ($I \gtrsim 10 \langle I \rangle$) exhibit large-amplitude EPW and secondary processes, such as obliquely side-scattered light, occur at sufficient amplitude to seed SRS in otherwise stable regions of plasma (seen in the finite backscattered SRS Poynting flux across the left of the box). The instantaneous $R_{SRS}$ at the left boundary is shown in the inset for cases (a–c) (black, blue, and red curves, respectively); the times plotted are 1.6 ps for the RPP (during the first large SRS burst), and 3.6 ps for the STUD pulse simulations [during the first, large SRS burst in (b)]. The central panels are $E_y^2$ over the leftmost 80 µm of the volume and indicate EPW amplitude correlated with the large bursts of SRS in (a) and (b).

In Fig. 2, we compare for cases (a–c) time-integrated hot electron flux per unit area exiting the simulation. The black curves are fluxes leaving the ±z boundaries from the left half of the simulation volume, the red curves, leaving ±z from the right of the volume, and the blue curves, leaving from the +z boundary. Prior work showed that large fluxes of tail electrons leaving the left of the volume (i.e., large black curves) are signatures of large-amplitude EPW with ensuing nonlinear self-focusing and filamentation and, ultimately, collective behavior among speckles [6, 7]. The three cases evince elevated distribution function tails as a consequence of trapping, though the RPP case traps not only far more tail electrons [60 × more than (c), 6 × more than (b)], but also shows far more side-scattered hot electrons exit nearest the laser entrance; moreover, hot electrons at very high energy ($E_K > 100$ keV) are present (absent for the STUD pulse beams). The use of STUD pulses has therefore decreased the number of hot electrons exchanged laterally among laser speckles, a key part of inter-speckle self-organization [7] and a possible contributor to capsule preheat in ICF experiments. In Fig. 3, we compare the angular spread of SRS light for the same cases as above. The use of STUD pulses leads to a dramatic overall reduction in SRS power (and hence, amplitude of the SRS seed in neighboring speckles). As with the RPP, the angular spread is finite, with most of the power falling outside the incident laser cone $|\theta| < 1/2f$ shown by the vertical lines. While the existence of coherent, oblique cones of backscattered light is not unique to this nonlinear regime—indeed, they appear in paraxial models with diffraction [2]—additional side-scatter results from trapping and EPW filamentation [5, 10] that is absent in fluid models; the use of STUD pulses reduces dramatically the levels of such side-scatter.

Finally, in Fig. 4, we show the dependence of $R_{SRS}$ on time-averaged incident laser intensity (left) and linear gain at the average intensity (right) for RPP and STUD pulses over a range of plasma and laser conditions. The use of STUD pulses reduces dramatically $R_{SRS}$ compared with RPP and ISI-like beams with the same time-averaged laser power. This is so even in cases of very high linear gain. As seen from comparison of the $R_{SRS}$ from the ISI-like points (the 8000×1, 1:1:1/2 and 9500×1, 1:1:1/2) and 5000×1, 1:1:1/2 cases, “healing time” is key: it is not enough to simply add bandwidth and spatial scrambling. By optimizing this healing
time for given “on+off” time and time-averaged power, STUD pulses may be optimized to significantly outperform ISI. From comparison of the 5000x1, 1:1:1/2 and the 5000x1, 1:1:1/2 cases, we find that spatial scrambling of the locations of the hot spots is also necessary to avoid effects of recurrence and correlation among successive hot spots [21]. Also, for fixed “on+off” time and time-averaged power, lengthening ‘off’ time requires shortening $\tau_{\text{spike}}$ and increasing the average speckle intensity correspondingly. Taken to an extreme, this can lead to enhanced trapping and associated EPW nonlinearity, evidenced by the 2000x1 datum shown in Fig. 4 (which also has significant hot electron sidescatter (not shown) compared with the 5000x1, 1:1:1/2 case at the same average power).

Examination of velocity distribution functions and EPW amplitudes shows strong trapping and only modest EPW damping between cycles. This trapping modifies $L_{\text{INT}}$ and suggests that possible threshold behavior may arise when $L_{\text{spike}}$ becomes less than $L_{\text{INT}}$ and when SRS goes from strong to weak damping. Consider the two 5000x1 and the 9500x1 STUD pulse cases at the highest intensity ($G = 11$). In the former, SRS in the largest amplitude hot spots (I $\gtrsim$ 10 I)) would be in the weak damping limit (WDL) if one applies the inferred $\nu_{\text{2}}$ from simulations ($\approx 0.1\nu_{\text{2}}^{\text{Max}}$), and $L_{\text{INT}} \approx 120$ $\mu$m. The 1:1:1/2 STUD pulse case, with the lowest $R_{\text{SRS}}$, has $L_{\text{spike}} \sim 0.37L_{\text{INT}}$ for these maximal speckles, i.e., STUD pulses much shorter than $L_{\text{INT}}$. In contrast, the 1:1:1 case has $L_{\text{spike}} \sim L_{\text{INT}}$. In the 9500x1, 1:1:1/2 ISI-like case, while $L_{\text{INT}} = 0.5L_{\text{spike}}$, reduction of $\nu_{\text{2}}$ causes the SRS to go to the WDL for an average intensity speckle, with correspondingly large $R_{\text{SRS}}$.

We have shown that SRS reflectivity may be lowered by more than an order of magnitude with the use of properly designed STUD pulses in settings where EPW trapping-induced nonlinearity is prevalent. This reduction stems from arresting large-amplitude EPW that give rise to cooperative behavior among laser speckles through the exchange of hot electrons and backscattered SRS waves, thus disallowing their self-organization. The substantial promise and generality of the STUD pulse technique [2] to a range of settings, including SRS in the strongly nonlinear, trapping regime considered here, would seem to impel serious consideration for how STUD pulses might be achieved in future ICF laser systems such as the Green option on the NIF or next-generation high-repetition-rate laser systems.

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[21] Because of how geometry affects multi-speckle coupling, transverse cross-speckle coupling through SRS side-loss hot electrons has been shown to be lower in 3D vs. 2D [7]. Moreover, the probability of spatial recurrence of hot spots is vastly smaller in 3D than in 2D. As a consequence, the advantages of STUD pulses in this nonlinear kinetic regime of SRS are expected to be more pronounced in more realistic, 3D geometry.