Storing, Retrieving, and Processing Optical Information by Raman Backscattering in Plasmas

I. Y. Dodin and N. J. Fisch
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543
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By employing stimulated Raman backscattering in a plasma, information carried by a laser pulse can be captured in the form of a very slowly propagating plasma wave that persists for a time long compared with the pulse duration. If the plasma is then probed with a short laser pulse, the information stored in the plasma wave can be retrieved in a second scattered electromagnetic wave. The recording and retrieving processes can conserve robustly the pulse shape, thus enabling the recording and retrieving with fidelity of information stored in optical signals.

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The possibility of trapping, storing, and retrieving a light pulse was recently confirmed in a series of experiments on laser pulse propagation through atomic vapor of rubidium atoms [1–3]. The ultraslow group velocity of electromagnetic waves compresses the laser pulse as it enters the vapor region and increases the pulse propagation time through the medium. Light storage is enabled by electromagnetically induced transparency (EIT) [4–6], wherein an external optical field switches the medium from opaque to transparent near an atomic resonance, letting the laser pulse into the medium. After the whole pulse has entered the system, the control field is turned off, converting the electromagnetic wave energy into the energy of spin excitations in atom vapor, which "stops" the pulse. The stopped laser pulse stored in atomic excitations can be accelerated up to the speed of light again by turning the control field on.

We suggest that similar trapping, storage, and retrieving of optical signals, with similar applications, can be implemented in a classical medium, namely, in cold plasma. As a laser pulse traverses the plasma, its information can be recorded in excited plasma waves with vanishing group velocity by means of Raman backscattering. What is remarkable is that, in principle, the stored information can then be retrieved with fidelity after a time much longer than the duration of the initial light pulse.

In contrast to the essentially instantaneous imprinting of the pulse structure into a medium [1], in Raman backscattering the recording and retrieving procedures are performed sequentially over a time on the order of the information pulse duration. The information pulse is scanned by a reference signal *gradually* providing that the optical field structure is recorded to the medium point by point. Thus, the slowing down the group velocity of a laser pulse in a nonlinear medium, which is essential for the EIT technique, is not required for making a "snapshot" of a laser pulse by means of Raman backscattering.

To show how the proposed recording-retrieving mechanism works, consider storing optical information in, say, the electromagnetic wave envelope A by employing a short counterpropagating pulse B, at the resonant Raman down-shifted frequency (see Fig. 1). The optical fields interact in cold underdense plasma via an electrostatic Langmuir wave at the plasma frequency ω_p produced by the beating of these two waves. The three-wave interaction, generalized to include somewhat detuned waves, is described by (see, e.g., Ref. [7])

$$a_t + a_x = bf, \qquad b_t - b_x = -af^*, \qquad f_t + i\delta\omega f = -ab^*. \tag{1}$$

Here a and b are the vector-potential envelopes of the light pulses A and B, respectively, in units $m_e c^2/e$, and f is the envelope of the Langmuir electrostatic field in units $(m_e c/e)\sqrt{\omega\omega_p/2}$, where $\omega = \omega_a \approx \omega_b \gg \omega_p$. The spatial coordinate x is measured in units $X = c\sqrt{2/\omega\omega_p}$, the time t is measured in units X/c, and the detuning $\delta\omega = \omega_a - \omega_b - \omega_p$ is measured in units c/X. The signal pulse A is assumed propagating in the positive x direction, and the reference pulse B in the negative x direction. Since the electromagnetic waves have frequencies large compared to the plasma frequency, their dispersion is

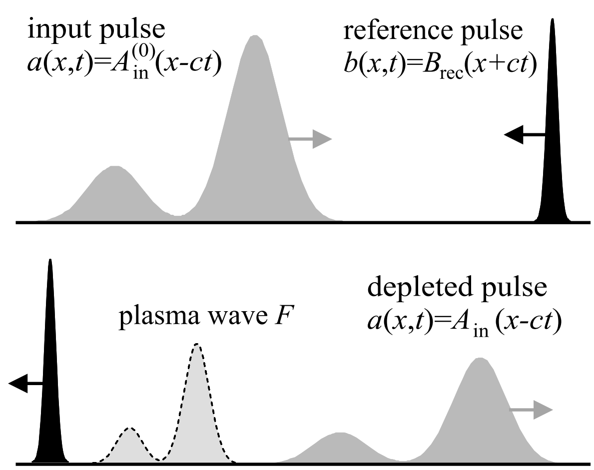

FIG. 1. Pulse recording through stimulated Raman backscattering.

negligible. For cold plasma, the Langmuir wave group velocity is also negligible.

In the simplest case, information is recorded when the input signal laser pulse $a_{\rm in}(x,t) = A_{\rm in}^{(0)}(x - t)$ interacts with a reference pulse $b_{\rm rec}(x,t) = \varepsilon_{\rm rec}\delta(x + t)$ short compared to the signal pulse (see Fig. 1). At low power, each wave may be considered as given, so that by integrating Eq. (1) we find the resulting plasma wave envelope, $F(x,t) = -\varepsilon_{\rm rec}^* A_{\rm in}^{(0)}(2x)\exp(-i\delta\omega x)$. Thus, the optical information is stored within the plasma in the form of simple oscillatory motion in a cold plasma wave, which is exactly half the original optical pulse length. Now suppose that a second short reference pulse $b_{\rm ret}(x,t) = \varepsilon_{\rm ret}\delta(x + t - \Delta)$ is injected into the plasma. Using Eqs. (1) again, assuming constant reference pulse and constant plasma wave, the backscattered signal $a_{\rm out}(x,t) = A_{\rm out}(x - t)$ is precisely the original signal $A_{\rm in}^{(0)}(x - t)$ attenuated and delayed by time Δ:

$$A_{\rm out}(x) = -\varepsilon_{\rm rec}^*\varepsilon_{\rm ret}\exp(-i\delta\omega\Delta)A_{\rm in}^{(0)}(x + \Delta)/2. \quad (2)$$

The result given by Eq. (2) contains the major idea of this paper, namely, the retrieving of the optical pulse information recorded into plasma. It remains to be seen that the information can be recorded and retrieved with fidelity under realistic conditions, namely, without the assumptions of infinitely small width and low power of the reference pulses, and in a plasma that experiences collisions or other nonideal effects.

Accordingly, suppose characteristic spatial scales $\Lambda_{\rm in}$ for the signal wave and σ for the reference wave such that $\Lambda_{\rm in} \gg \sigma$. Assuming the reference pulse $b(x,t) = B(x + t)$ fixed, we find

$$\begin{aligned} A(x,t) &= g_a^{(c)}(x)\cos\phi(x + 2t) + g_a^{(s)}(x)\sin\phi(x + 2t), \\ F(x,t) &= g_f^{(c)}(x)\cos\phi(x + t) + g_f^{(s)}(x)\sin\phi(x + t). \end{aligned} \quad (3)$$

Here, $F(x,t) = f(x,t)e^{i\delta\omega t}$; $\phi(\xi) = \frac{1}{\sqrt{2}}\int_{-\infty}^{\xi}|B(\eta)|\,d\eta$ is a function with the spatial scale σ; the functions $g_a^{(c)}(x) = A(x, t \to -\infty)$ and $g_f^{(c)}(x) = F(x, t \to -\infty)$ have characteristic spatial scale $\Lambda_{\rm in}$; the functions $g_a^{(s)}$, $g_f^{(s)}$ with spatial scale $\Lambda_{\rm in}$ are to be expressed through $g_a^{(c)}$, $g_f^{(c)}$ by substituting solution (3) into Eqs. (1). Thus, for the recording process, when the initial conditions for (3) satisfy $A_{\rm in}(x, t \to -\infty) = A_{\rm in}^{(0)}(x)$, $F(x, t \to -\infty) \equiv 0$, we find the distorted amplitude of the input laser pulse [8]

$$A_{\rm in}(x,t) = A_{\rm in}^{(0)}(x)\cos\phi_{\rm rec}(x + 2t). \quad (4)$$

Note that the input pulse profile is now multiplied by the factor $\cos\lambda_{\rm rec}$, where $\lambda_{\rm rec} = \phi_{\rm rec}(+\infty)$. The interaction preserves the original shape of the laser pulse $A_{\rm in}^{(0)}(x)$. More importantly, energy proportional to $(\sin\lambda_{\rm rec})^2$ is converted to the energy of the plasma wave F, where the full information about the input pulse is now stored in

$$\begin{aligned} F(x,t) = {}&[-\sqrt{2}\exp(-i\theta_{\rm rec} - i\delta\omega x)] \\ &\times A_{\rm in}^{(0)}(2x)\sin\phi_{\rm rec}(x + t), \end{aligned} \quad (5)$$

where $\theta_{\rm rec}$ is the constant phase of the recording signal $b_{\rm rec}$. The conservation law

$$2|a(x,t)|^2 + |f(x,t)|^2 = 2|A_{\rm in}^{(0)}(2x)|^2, \quad (6)$$

following from (4) and (5), is a Manley-Rowe relation, providing the conservation of the total number of quanta in the laser pulse $A_{\rm in}$ and the plasma wave F. Equation (6) is obtained under the assumption of small ratio $\sigma/\Lambda_{\rm in}$, so that slowly changing amplitudes of the information pulses a and f must be evaluated at $x \approx -t$, where the narrow reference pulse is currently located.

The stored wave (5), proportional to the twice-compressed profile of the input signal, is essentially a static snapshot of the input pulse imprinted into the plasma. Figure 2 shows a comparison between the analytical result (5) and a numerical solution of the nonlinear Eqs. (1) with good agreement even for $\sigma/\Lambda_{\rm in}$ as large as 0.2. In Fig. 2, $\lambda_{\rm in}$ measures the input pulse *area,* $\lambda_{\rm in} \equiv \int A_{\rm in}^{(0)}(x)\,dx$. In the case offered here, with $\lambda_{\rm in} = 1$, the reference pulse distortion and the loss of recording quality corresponding to it are insignificant.

The maximal amplitude of the recorded wave $F(x, t \to +\infty) \propto A_{\rm in}^{(0)}(2x)\sin\lambda_{\rm rec}$ is achieved at $\lambda_{\rm rec} = \pi(n + 1/2)$, where n is an integer. For this type of reference signal, the pulse recording results in the complete depletion of the input electromagnetic wave envelope $A_{\rm in}$, since $A_{\rm in}(x, t \to +\infty) \propto \cos\lambda_{\rm rec} = 0$.

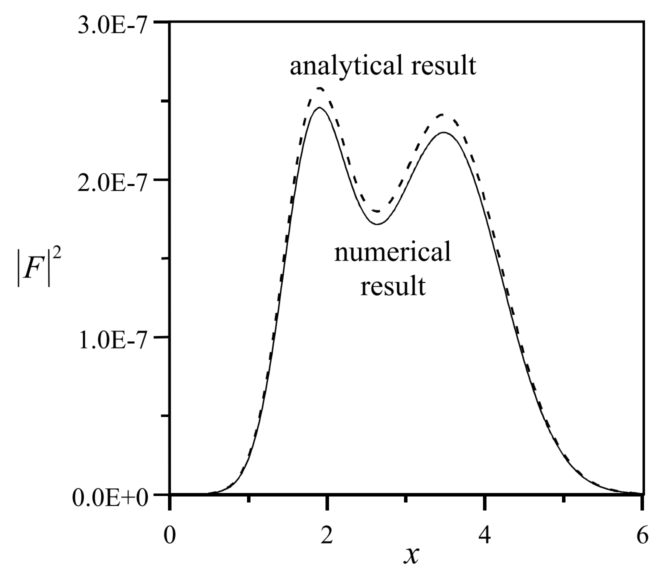

FIG. 2. Recorded plasma wave sample profile: analytical results (dashed line) and numerical calculations (solid line) for the recording of a two-hump information pulse ($\lambda_{\rm in} = 2 \times 10^{-3}$), with a reference pulse having $\lambda_{\rm rec} = 1$, $\sigma/\Lambda_{\rm in} \sim 0.2$.

Values $\lambda_{rec} \leq O(1)$ cover the whole amplitude range of the recorded signals F. In this regime, the validity condition for the developed theory can be written as $\lambda_{in}^2 \ll 1$, providing the insignificance of the recording pulse distortion caused by the finite amplitude of both pump wave A_{in} and plasma wave F.

Pulse retrieving from plasma is the inverse process to recording, but is based on a similar technique (Fig. 3). Consider the interaction of a short retrieving pulse $b_{ret}(x,t) = B_{ret}(x + t)$ with the plasma wave F stored in plasma. The initial conditions for (3) are then given by $A_{out}(x, t \to -\infty) \equiv 0$, $F(x, t \to -\infty) = F^{(0)}(x)$, where A_{out} is the information wave generated as a result of the nonlinear interaction between the reference pulse and the plasma wave. The solution for the information waves under the assumption of the fixed shape of $B_{ret}(x) = |B_{ret}(x)| \exp(i\theta_{ret})$, $\theta_{ret} = \text{const}$, is then given by

$$\begin{aligned} F(x,t) &= F^{(0)}(x)\cos\phi_{ret}(x + t), \\ A_{out}(x) &= [\exp(i\delta\omega x/2 + i\theta_{ret})/\sqrt{2}] \\ &\quad \times F^{(0)}(x/2)\sin\phi_{ret}(x + 2t), \end{aligned} \tag{7}$$

where F and A_{in} again satisfy the Manley-Rowe relation (6). Similar to the recording procedure, pulse retrieving preserves the shape of the information pulse, providing an output signal with the same profile as given by the initial conditions, though twice stretched in x. In principle, this straightforward way of pulse conversion on the light acceleration stage can also be used for constructing electromagnetic pulses of the required shape. Assume one is able to design the plasma wave profile $F^{(0)}$ by some external means. The plasma wave does not propagate at high speed, and thus the shape design for plasma oscillations might be easier to implement when comparing it with the construction of the light pulse shape "by hand" while the light pulse is propagating. Further, by applying the retrieving procedure, this artificially designed pulse is accelerated up to the speed of light preserving the plasma wave profile.

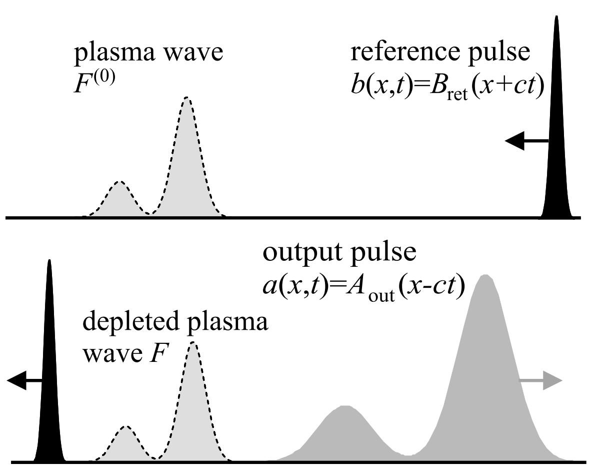

FIG. 3. Pulse retrieving through stimulated Raman backscattering.

The light pulse of the required shape would be the result of the process, which might be useful for various applications where the laser pulse structure is critical.

Step-type solutions produced with $\lambda_{ret} = \pi(n + 1/2)$, where n is an integer, provide the largest amplitude of the output signal A_{out}. However, since the amplitude of the plasma wave remaining after the interaction vanishes, a single step-type retrieving prohibits further information retrieving by more reference pulses. On the other hand, this feature might be of practical interest when the plasma oscillations need to be attenuated by external means. As long as the validity conditions for the developed theory remain valid, one can "clean" the plasma by scanning it with retrieving pulses having $\lambda_{ret} = \pi(n + 1/2)$. Then, the energy of the plasma oscillations is converted into the energy of electromagnetic oscillations propagating out of plasma at the speed of light. Therefore, one can cool the plasma by means of external laser radiation in the form of short reference pulses if the strength of these pulses is chosen properly.

The validity condition for this theory of pulse retrieving to remain valid is given by $(\int F^{(0)}(x)\,dx)^2 \ll 1$, which is satisfied automatically if $F^{(0)}$ is recorded into the plasma with condition $\lambda_{in}^2 \ll 1$ satisfied.

Finally, consider the combined recording-retrieving procedure, when the signal A_{in} is first recorded into plasma and then retrieved back as a signal A_{out} by reference pulses shifted in time by a time interval Δ with respect to each other. From (5) and (7), one realizes that the output signal represents an attenuated and delayed modification of the input signal $A_{in}^{(0)}$, exactly preserving the shape of the latter:

$$A_{out}(x) = \alpha A_{in}^{(0)}(x + \Delta),$$

where α is the constant transformation coefficient given by $\alpha = -\sin\lambda_{rec}\sin\lambda_{ret}\exp[-i(\delta\omega\Delta + \theta_{rec} - \theta_{ret})]$. Thus, provided that both $\lambda_{rec} = \pi(n_1 + 1/2)$ and $\lambda_{ret} = \pi(n_2 + 1/2)$, the recording-retrieving procedure preserves not only the pulse shape but also its energy.

Under the adopted approximation of collisionless cold plasma, the pulse storing time Δ does not impact the quality of the profile reconstruction. In practice, however, the value of Δ allowing a high quality of the output signal is limited by the decay of the plasma oscillation profile F. The latter is determined by Coulomb collisions, Landau damping, and signal distortion caused by the finite group velocity of the recorded plasma wave neglected in our model. However, as seen from Table I, in a realistic temperature and frequency range, millimeter-sized laser pulses can be stored in plasmas without significant distortion of their profiles on time scales long compared to the duration of the information pulses. For example, note from Table I that the information in a 4-ps-long pulse of 10 μm radiation can be stored in a plasma with density 5×10^{17} cm^{-3} and length just 1.2 mm. If the plasma temperature is about 200 eV, then the information can be stored for about

TABLE I. Two examples of sets of parameters for the proposed laser pulse recording-retrieving experiment.

Parameter	Experiment 1	Experiment 2
Wavelength $2\pi c/\omega$, μm	10	100
ω_p/ω	0.2	0.2
$\sigma/\Lambda_{\mathrm{in}}$	0.2	0.1
Electron temperature, eV	200	200
Pulse duration Λ, ps	4	170
Pulse length, mm	1.2	50
Electron density, cm^{-3}	5×10^{17}	5×10^{15}
Maximal possible time of pulse storing ($\Delta_{\max}/\Lambda_{\mathrm{in}}$)	20	50
Reference pulses intensity, $\mathrm{W/cm}^2$	5×10^{12}	1×10^{10}
Information pulse maximal intensity, $\mathrm{W/cm}^2$	2×10^{11}	1×10^{8}

20 pulse durations, or for about 80 ps. For THz radiation, a longer, more rarified plasma can be used.

The linear regime of recording and retrieving ($\lambda_{\mathrm{rec}}, \lambda_{\mathrm{ret}} \ll 1$) might be of further interest, because of the possibility to process analog information stored in a laser pulse. Assume then zero detuning ($\delta\omega = 0$). Consider now the recording procedure, although analogous results can also be obtained for the stage of pulse retrieving. For a weak reference pulse, the input signal is not distorted significantly, so that, directly from Eqs. (1), one can see that the recorded plasma wave profile is equal to the convolution of the electromagnetic pulse profiles:

$$F(x,t) = -\int_{-\infty}^{x+t} dt'\, A_{\mathrm{in}}^{(0)}(2x - t') B_{\mathrm{rec}}^{*}(t')\,.$$

Therefore, by varying the shape of the reference signal B_{rec}, it is possible to record not only the original profile of the input pulse but its various linear transformations as well. For example, by taking the reference pulse proportional to the derivative of the delta function, $B_{\mathrm{rec}}(x) = \varepsilon_{\mathrm{rec}}\,\delta'(x)$, one obtains the stored plasma wave amplitude

$$F(x) = -\varepsilon_{\mathrm{rec}}^{*}[dA_{\mathrm{in}}^{(0)}(\xi)/d\xi]_{\xi=2x}\,,$$

proportional to the derivative of the input signal. Alternative shapes of $B_{\mathrm{rec}}(x)$ and $B_{\mathrm{ret}}(x)$ allow one to perform other integral conversions of the information pulse on the stage of recording or retrieving correspondingly. In this regard, the use of a known reference pulse is similar to its use in coherent anti-Stokes Raman scattering (CARS) techniques or frequency-resolved optical gating (FROG) [9] techniques, except that here the reference pulse is used to process the signal, rather than to inform on it.

In summary, we report the possibility of trapping, storing, and retrieving light pulses by means of stimulated Raman backscattering (SRBS) in cold plasmas. Information can be stored in the plasma for a time long compared to the input pulse duration and retrieved on demand. Additional applications of the recording-retrieving procedure might include plasma cooling (or signal erasing) or construction of an electromagnetic pulse of a given shape via external control over the plasma wave profile. Moreover, by freezing optical information in the slow-moving plasma wave, we not only can retrieve this information intact but we might also process this optical signal, such as, for example, by extracting the derivative of the pulse form. These types of manipulation of an optical signal may provide new tools for the construction of precise optical pulse shapes for a variety of physical applications [10]. It is important to note that the technique described here should be applicable not only for plasmas but for other Raman media as well, such as liquids, gases, or fibers.

Finally, since the recording and retrieving procedures allow a certain analog processing of the laser pulse shape, plasma channels can be used not only as analog memory cells, but also as processors performing certain mathematical operations on shapes of laser pulses. It is hoped that these interesting effects made possible by SRBS in cold plasmas and other Raman media might provide new techniques in optical communications technology or analog computing.

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