**PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073**

PPPL-3645 **PPPL-3645**
UC-70

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by

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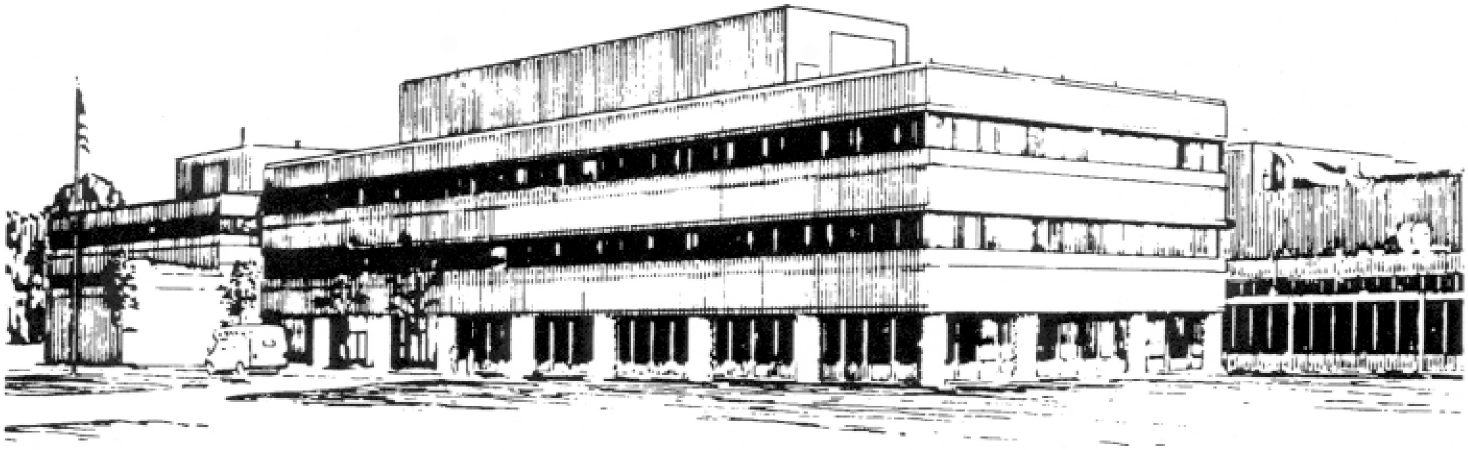
January 2002



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

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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 large 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.

PACS numbers: 52.35.Mw, 52.38.Bv

The possibility of trapping, storing and retrieving the light pulses was recently confirmed in 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 large compared with the duration of the initial light pulse.

To show this, consider storing optical information in, say, the electromagnetic wave envelope *A* by employing a short counterpropagating pulse *B*, at the resonant Raman downshifted frequency. 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. [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 $\omega = \omega_a \approx \omega_b >> \omega_p$. 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 auxiliary pulse B in the negative x-direction. Since the electromagnetic waves have frequencies large compared to the plasma frequency, their dispersion is 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 $a_{in}(x,t) = A_{in}^{(0)}(x-t)$ interacts with an auxiliary pulse $b_{rec}(x,t) = \varepsilon_{rec}\delta(x+t)$ short compared to the signal pulse (see Fig. 1). At low power, each wave may be considered as given, so that integrating Eq. (1), we find the resulting plasma wave envelope, $F(x,t) = -\varepsilon_{rec}^{*} A_{in}^{(0)}(2x)\exp(-i\delta\omega x)$. 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 auxiliary pulse $b_{ret}(x,t) = \varepsilon_{ret}\delta(x+t-\varDelta)$ is injected into the plasma. Using Eqs. (1) again, assuming constant auxiliary pulse and constant plasma wave, the backscattered signal $a_{out}(x,t) = A_{out}(x-t)$ is precisely the original signal $A_{in}^{(0)}(x-t)$ attenuated and delayed by time $\varDelta$:

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

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

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

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

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 Λ_{in}; the functions $g_a^{(s)}$, $g_f^{(s)}$ of the spatial scale Λ_{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 $A_{in}(x, t\to-\infty) = A_{in}^{(0)}(x)$, $F(x, t\to-\infty) \equiv 0$, we find the distorted amplitude of the input laser pulse

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

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

$$F(x,t) = \left[-\sqrt{2}\exp(-i\theta_{rec} - i\delta\omega x)\right] A_{in}^{(0)}(2x)\sin\phi_{rec}(x+t), \tag{5}$$

where θ_{rec} is the constant phase of the recording signal b_{rec}. The conservation law

$$\partial_t \left(2|A_{in}|^2 + |F|^2\right) \equiv 0, \tag{6}$$

following from (4) and (5), is a Manley-Rowe relation, providing the conservation of the total number of quanta in the laser pulse A_{in} and the plasma wave F.

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. Fig. 2 shows a comparison between the analytical result (5) and a numerical solution of the nonlinear Eqs. (1) with good agreement even for σ/Λ_{in} as large as 0.2. In the case offered here, the auxiliary pulse distortion and the loss of recording quality corresponding to it are insignificant.

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

Values $\lambda_{rec}\le O(1)$ cover the whole amplitude range of the recorded signals F. In this regime, the validity condition for the developed theory can be written as

$$\lambda_{in}^{2}=\left(\int A_{in}^{(0)}\left(x\right)dx\right)^{2}<<1, \tag{7}$$

providing the insignificance of the recording pulse distortion caused by the finite amplitude of both pump wave A_{in} and the plasma wave F. In the presence of a finite-amplitude resonant plasma noise F_n, the additional conditions $\lambda_{rec}\lambda_{ns}<<\lambda_{in}$, $\lambda_n\lambda_{ns}<<1$, $\lambda_{in}\lambda_{ns}<<\lambda_{rec}$ for quality recording are required. Here, $\lambda_{ns}\sim F_n\Lambda_{in}$ and $\lambda_n=\int F_n\left(x\right)dx\sim F_n\Lambda_n$, where $\Lambda_n\ge O\left(\Lambda_{in}\right)$ is the full path of a laser pulse inside the noisy plasma.

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

$$F\left(x,t\right)=F^{(0)}\left(x\right)\cos\phi_{ret}\left(x+t\right),$$

$$A_{out}\left(x\right)=\left[\exp\left(i\delta\omega x/2+i\theta_{ret}\right)/\sqrt{2}\right]F^{(0)}\left(x/2\right)\sin\phi_{ret}\left(x+2t\right), \tag{8}$$

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 the 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 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 comparing with construction of the light pulse shape "by hands" 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. 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 $\lambda_{ret}=\pi\left(n+1/2\right)$, *n* is an integer, provide the largest amplitude of the output signal A_{out}. However, since the amplitude of the plasma wave remained after the interaction is equal to zero, a single step-type retrieving prohibits further information retrieving by more auxiliary 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 $\lambda_{ret} = \pi\left(n + 1/2\right)$. 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 auxiliary pulses if the strength of these pulses is chosen properly.

The validity condition for the developed theory of pulse retrieving to remain valid, similar to the condition of quality recording (7), is given by

$$\lambda_s^2 = \left(\int F^{(0)}\left(x\right)dx\right)^2 << 1,$$

which is satisfied automatically in case if $F^{(0)}$ was recorded into plasma with condition (7) satisfied. In the presence of a finite-amplitude resonant noise F_n, the additional conditions $\lambda_{ns} << \lambda_s$, $\lambda_n \lambda_{ns} << 1$ for quality retrieving are required.

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 auxiliary pulses shifted in time on a time interval Δ with respect to each other. From (5) and (8), one gets that the output signal represents an attenuated and delayed modification of the input signal $A_{in}^{(0)}$ exactly preserving the shape of the latter:

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

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

Under the adopted approximation of collisionless cold plasma, the pulse storing time Δ does not impact the quality of the profile reconstruction. For real physical system, however, the value of Δ allowing the high quality of the output signal is limited by the decay of the plasma oscillations 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 1, in a certain temperature and frequency range, centimeter-size laser pulses can be stored in plasmas without significant distortion of their profiles on time scales large compared with the duration of the information pulses.

The linear regime of recording and retrieving ($\lambda_{rec}, \lambda_{ret} << 1$) might be of additional interest because of the possibility to process the analogue information stored in a laser pulse. Assume zero detuning ($\delta\omega = 0$) and focus on the recording procedure though analogous results can be achieved on the stage of pulse retrieving, too. For weak auxiliary 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 pulses profiles:

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

Therefore, varying the shape of the auxiliary 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, taking the auxiliary pulse proportional to the derivative of delta-function, $B_{rec}(x) = \varepsilon_{rec} \delta'(x)$, one gets the stored plasma wave amplitude

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

proportional to the derivative of the input signal. Alternative shapes of $B_{rec}(x)$ and $B_{ret}(x)$ allow performing other integral conversions of the information pulse on the stage of recording or retrieving correspondingly.

In summary, we report the possibility of trapping, storing and retrieving the light pulses by means of stimulated Raman backscattering (SRBS) in cold plasmas. Information can be stored in the plasma for a time large compared with the input pulse duration and retrieved on demand. Additional applications of the recording – retrieving procedure might include plasma cooling and constructing the electromagnetic pulses of a given shape via external control over the plasma wave profile. Moreover, by freezing optical information in the slow moving plasma wave, we can not only retrieve this information intact, but we might also process this optical signal, such as, for example, 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 [8]. 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 certain analogue processing of the laser pulse shape, plasma channels can be used not only as analogue 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 enable new techniques in optical communications technology or analogue computing.

This work was supported by the US DOE, under contract DE-AC02-76 CHO3073.

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Table 1. Examples of the pulses and plasma parameters for the proposed laser pulse recording-retrieving experiment

ω_p / ω	0.1	0.2	0.2
$\sigma / \Lambda_{in} = 0.1$	0.1	0.1	0.1
Wavelength $2\pi c/\omega$, μm	100	100	200
Electron temperature, eV	50	200	150
Pulse duration Λ_{in}, ps	330	170	330
Pulse length, cm	10	5	10
Electron density, cm^{-3}	10^{15}	$5 \cdot 10^{15}$	10^{15}
Maximal possible time of pulse storing ($\Delta_{\max} / \Lambda_{in}$)	30	70	100
Energy flux density for the auxiliary pulses, W/cm^2	10^{10}	$2 \cdot 10^{10}$	$5 \cdot 10^{9}$
Maximal energy flux density for the input pulse, W/cm^2	10^{8}	$2 \cdot 10^{8}$	$5 \cdot 10^{7}$

FIGURE CAPTIONS:

FIG. 1. A conceptual scheme of pulse recording by means of stimulated Raman backscattering

FIG. 2. Recorded plasma wave sample profile: analytical results (dashed line) and numerical calculations (solid line):

$$A_{in}^{(0)}(x) = 10^{-3}(2\pi)^{-1}\left[2\Lambda_1^{-1}\exp\left(-(x-3.5)^2/2\Lambda_1^2\right) + 0.8\Lambda_2^{-1}\exp\left(-x^2/2\Lambda_2^2\right)\right],$$

$$\Lambda_1 = 2,\ \Lambda_2 = 1,\ B_{rec} = \lambda_{rec}\exp\left(-x^2/2\sigma^2\right)\Big/\sqrt{\pi\sigma^2}\ ,\ \lambda_{rec} = 1,\ \sigma = 0.2$$

FIG. 3. A conceptual scheme of pulse retrieving by means of stimulated Raman backscattering

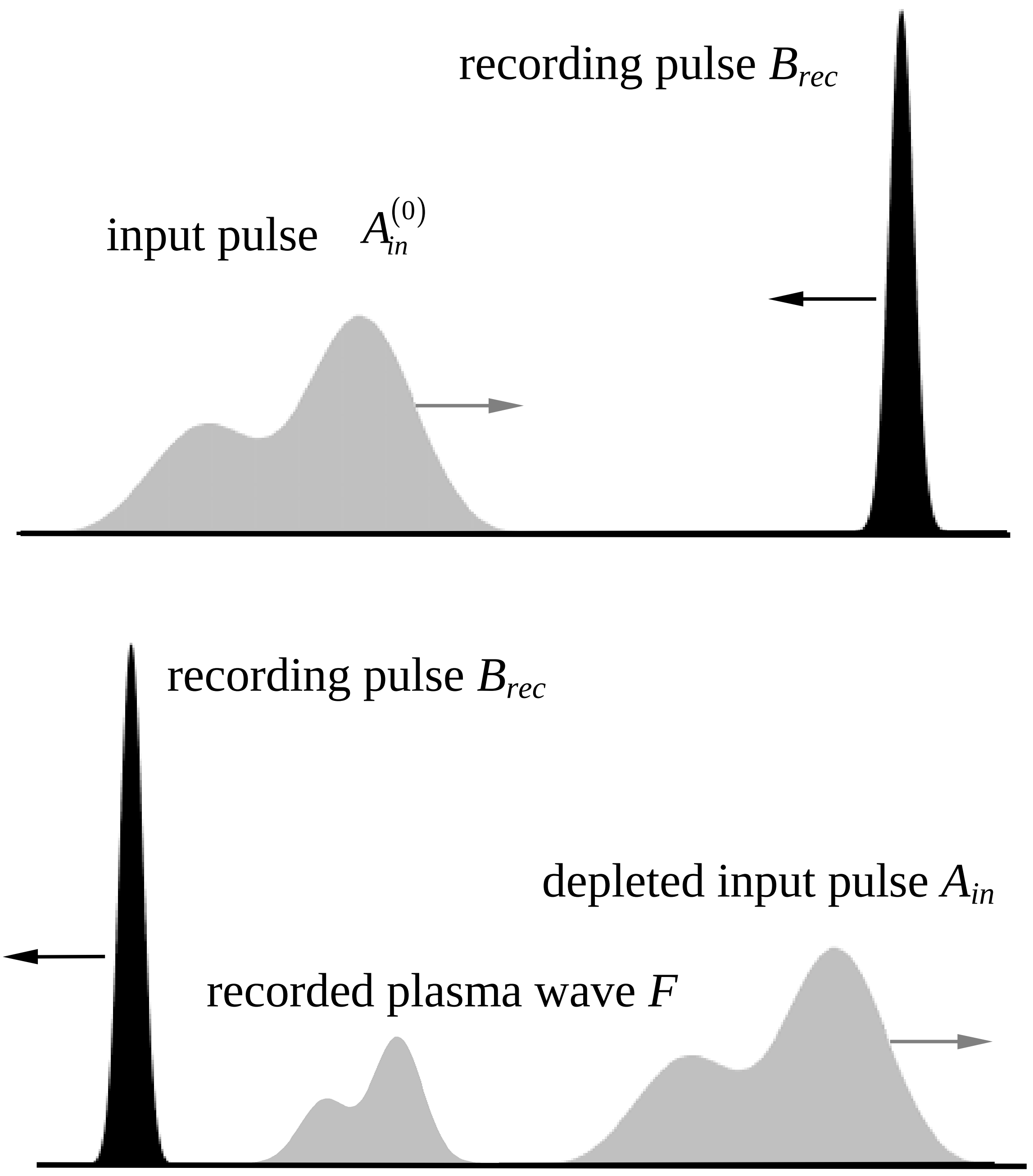
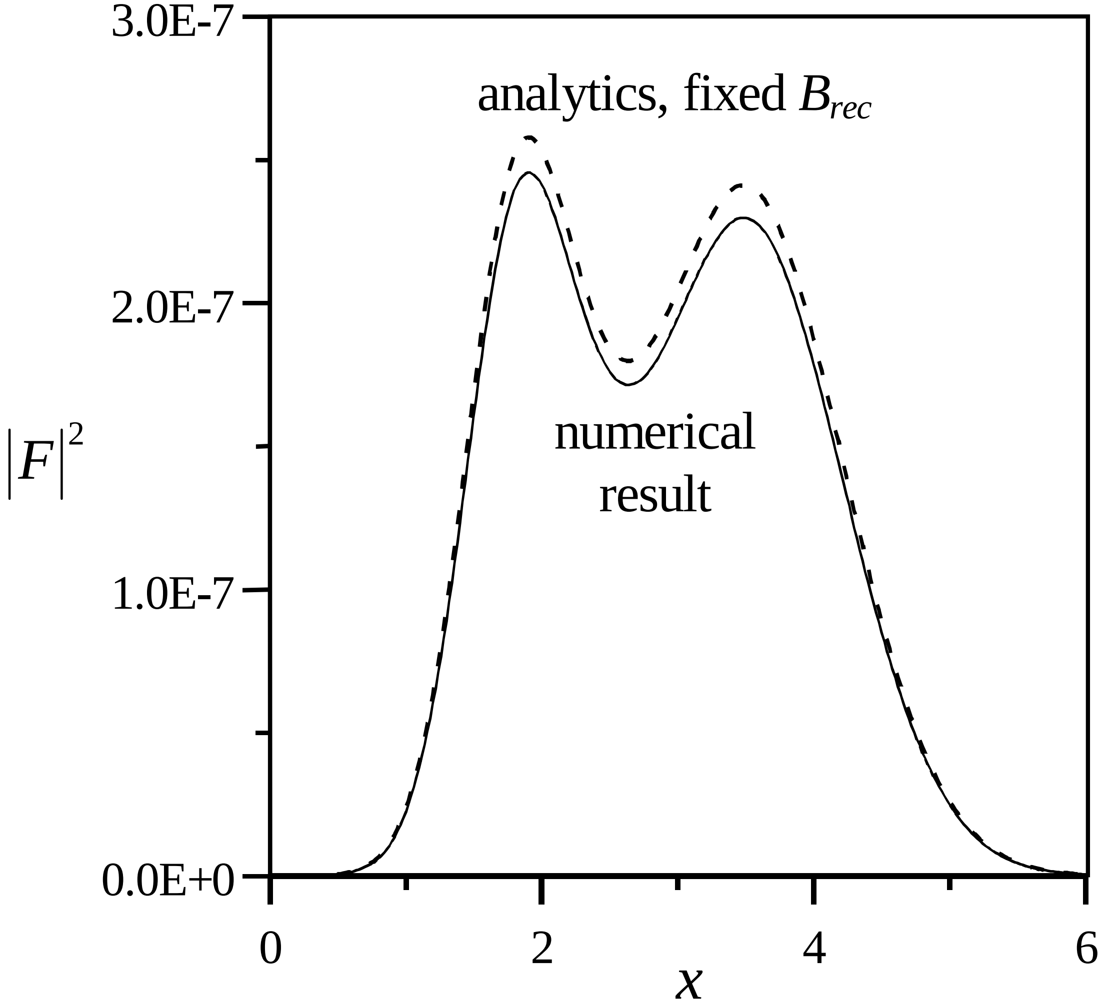

recording pulse B_{rec}
input pulse $A_{in}^{(0)}$
recording pulse B_{rec}
depleted input pulse A_{in}
recorded plasma wave F

FIG. 1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2.0E-7
1.0E-7
0.0E+0
$|F|^2$
analytics, fixed B_{rec}
numerical result
0
2
4
6
x

FIG. 2

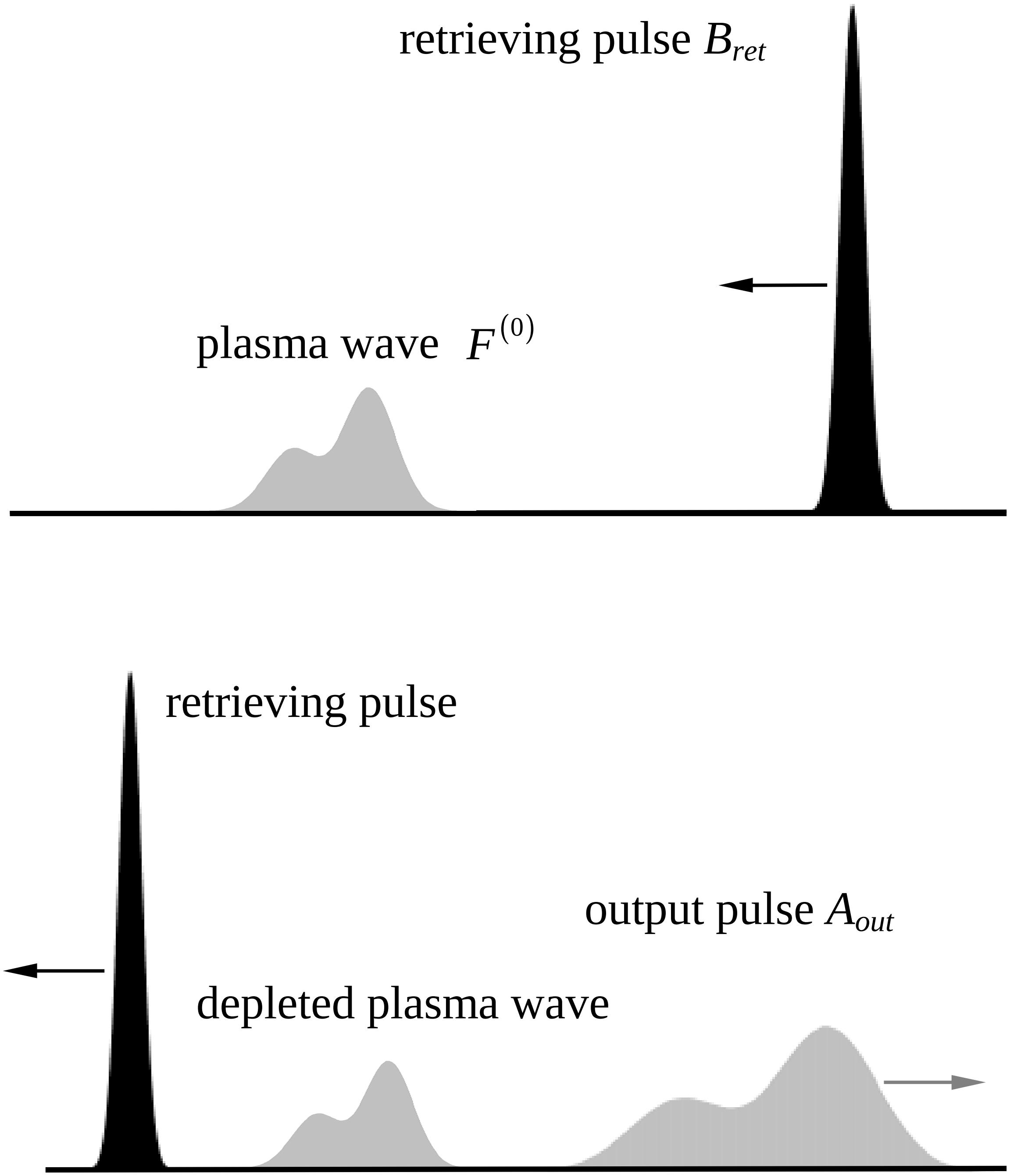
retrieving pulse B_{ret}
plasma wave $F^{(0)}$
retrieving pulse
output pulse A_{out}
depleted plasma wave

FIG.3

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