Backward Raman amplification of ionizing laser pulses

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Ultraintense laser pulse compression by means of backward Raman scattering of a laser pump in plasma might be accomplished alternatively, and possibly technologically more simply, at ionization fronts. [DOI: 10.1063/1.1400791]

The backward Raman amplification (BRA) of powerful lasers has recently reattracted much attention because of the new proposal,[1] envisioning BRA use for achieving laser energies and powers significantly higher than presently available through the most advanced chirped pulse amplifiers (CPA), as given in Ref. 2. The higher energies and powers might be achieved, even in much smaller devices. The BRA is also highly efficient, producing both complete pump depletion and strong contraction of the amplified pulse.

The proposed working medium in new BRA devices is plasma, capable of tolerating ultrahigh laser intensities within times shorter than it takes for filamentation instabilities to develop. The BRA in plasma is fast enough to reach within such times nearly relativistic pumped pulse intensities, say $10^{17}\,\mathrm{W/cm^2}$, for $\lambda = 1\ \mu$m-wavelength radiation. Such a nonfocused intensity would be 10^5 times higher than currently available. Moreover, since the peak intensity scales like $1/\lambda^2$, even much higher laser intensities might become feasible when appropriate x-ray pump lasers are developed.

Traditional BRA was plagued by parasitic forward Raman amplification (FRA) of noise (see, for example, Ref. 3), which has a higher rate than the BRA in gases, liquids, and solids. In plasma, however, the BRA is faster than the FRA (see, for example, Ref. 4), which both alleviates and shifts the problem. A dangerous instability is then the BRA of the pump to noise, as the pump traverses the plasma layer toward the seed pulse. This instability can be suppressed by detuning the resonance appropriately, even as the desired amplification process persists with high efficiency due to nonlinear resonance broadening, as shown in Ref. 5.

What we suggest now is an alternative scheme where such a problem does not even appear and where preformed plasma is not needed. In this alternative scheme, the pump propagates toward the seed pulse through a layer of traditional medium, say, gas. The layer width is smaller than the nonlinear refraction and Raman lengths in this medium. The pump intensity is not sufficient to ionize the medium. The ionization is produced by the pumped pulse, which is more intense than the pump. For example, intensities about $10^{15}\,\mathrm{W/cm^2}$, for $\lambda = 1\ \mu$m-wavelength radiation, may be sufficient to initiate the field ionization. The plasma so produced mediates energy transfer between the counterpropagating pulses, like in the original "fast compression" scheme of Ref. 1. The pump energy is then consumed by the pulse and strongly compressed within a short propagation distance because of an enhanced coupling between the pump and pumped laser.

To accomplish this scheme, the pump must not be so intense as to experience deleterious nonlinear self-modification effects during the propagation through the medium layer. But the pump should be intense enough to compensate for the pumped pulse ionization losses without a serious reduction in the BRA efficiency.

The BRA effect might also be achieved with only a single laser. For instance, one can propagate an appropriately chirped pump through a gas at power levels that do not produce copious ionization. The wave can then be reflected at the exit boundary, so that the combined fields of the reflected wave and the incident pump wave ionize gas to form a plasma. A sharp enough ionization front might then initiate efficient BRA. The sharp front is needed to provide the frequency bandwidth sufficient for the BRA seeding, so that, for this subscheme, the respective front duration should not be much larger than the inverse plasma frequency. A sharp front might also prevent the generation of deleterious superluminous precursors to the amplified laser seed, as described in Ref. 6. Yet another possibility is that the pump may undergo FRA and frequency downshift in a gas, and then be reflected back at the exit. It can then serve as a counterpropagating seed, ionizing the gas, at first with assistance from the pump and then by itself.

Traditional BRA is also plagued by the FRA of noise by the pumped pulse. Although much alleviated by the favorable backward-to-forward Raman gain ratio, this problem persists nevertheless in plasma-based BRA. This is because the forward-scattered signal propagates together with the parent laser, and so has more distance to grow than does the backscattered signal that quickly passes through a short parent pulse. This FRA imposes the major theoretical limit on the peak intensity of output laser pulse in the fast compression scheme of Refs. 1, 5. In the alternative scheme considered here, the respective limitation may be even stricter, because of possible strong seeding of FRA in ionization fronts (see, for example, Ref. 7).

A way of suppressing the parasitic FRA of the pumped laser pulse, identified in Ref. 8, may be even more useful for the BRA of ionizing pulses. The idea is to combine two different detuning mechanisms that strongly detune the parasitic FRA of the pumped laser pulse, but nearly compensate each other with respect to the useful resonance. A high level of noise, seeding the parasitic FRA of the pumped laser pulse, can then be tolerated in BRA devices without being significantly amplified. The useful amplification process can persist there with a high efficiency. The method basically removes the FRA imposed theoretical limit for the BRA output intensity. In our alternative scheme of BRA of ionizing laser pulses, it might be possible even to simplify the method by using the natural ''blue shift'' of laser frequency in ionization fronts (see, for instance, Ref. 9) as a detuning mechanism.

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