# Coherent amplification of femtosecond pulses with passive enhancement cavities

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**Abstract:** We demonstrate a general technique for amplification of femtosecond pulses through coherent buildup in an external cavity. Intracavity pulse enhancement >110 times is demonstrated for 49-femtosecond pulses with up to 50 % dumping efficiency.

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Many applications require higher pulse energies than are typically available from standard femtosecond laser oscillators. Pulses that have microjoule energy, a duration of 10 – 50 femtosecond, and a high repetition frequency are particularly desirable. Without active amplification, pulse energies can be enhanced using cavity dumping and extended cavity oscillator designs [1,2]. Femtosecond pulse energies can be significantly increased inside "femtosecond enhancement cavities" while still maintaining high repetition rates [3]. Intracavity experiments may be performed so long as the cavity is engineered to compensate for group-delay dispersion (GDD) that would otherwise distort the pulse and limit the intracavity field [4,5]. For external cavity applications one employs a fast switch in the form of a Brewster-angled Bragg cell to dump out the stored pulse. Previous work has demonstrated this principal with picosecond pulses [6] in which the role of cavity dispersion and the effects of the carrier-envelope offset frequency ($f_{ceo}$) were negligible. Here we extend the technique into the sub-50 femtosecond regime and demonstrate results for "noise-free" amplification of femtosecond pulses by coherently storing broadband pulses inside a high finesse, passive optical cavity. This route of pulse enhancement offers phase controlled femtosecond pulses at high repetition rates and pulse energies from 100's of nanojoules up to the microjoule level.

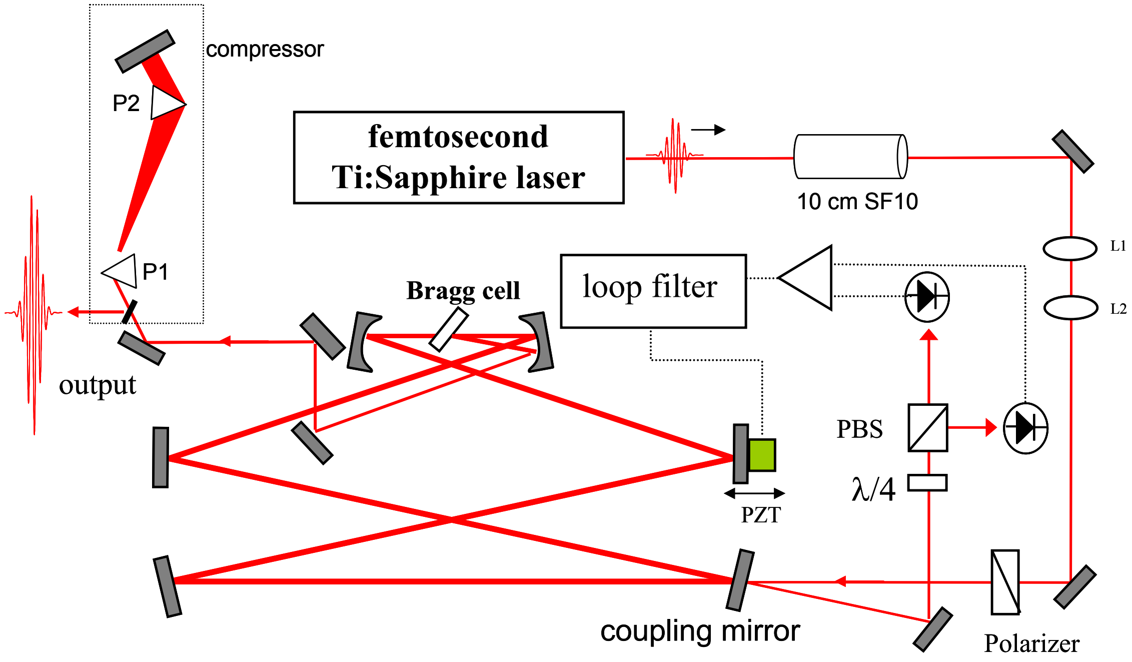

Fig. 1. Schematic of femtosecond pulse amplification with an external passive ring resonator.

Figure 1 shows the schematic setup of our passive femtosecond pulse amplifier. The femtosecond enhancement cavity incorporates low loss negative group delay dispersion mirrors to provide a high cavity finesse and zero net cavity group delay dispersion. The cavity is placed in a vacuum chamber and it is pressure tuned for fine adjustment of the cavity dispersion. The cavity length is actively controlled to allow stable coupling between the cavity modes and the corresponding femtosecond comb structure [5,6]. The overall cavity finesse is about 400, with the input coupling mirror's transmission coefficient of 0.8%, designed to provide an optimum power coupling ("impedance matching"). The single-pass loss through the 3 mm fused silica Bragg cell (when it's off) is ~ 0.4%. Self-phase modulation and Raman nonlinearities in the fused silica Bragg cell tend to shift and distort the pulse spectrum. Sufficient stretching of the incident pulses to minimize the peak intracavity intensity allows linear enhancement of the pulse spectrum and simple recompression of the output pulses. In these initial results a 10 cm piece of SF 10 glass and various optics stretched the incident pulse from ~ 47 fs to > 400 fs. This modest stretching increased the intracavity energy that could be built up without pulse distortion and demonstrates the technique can be scaled to higher energies with adequate pulse stretching.

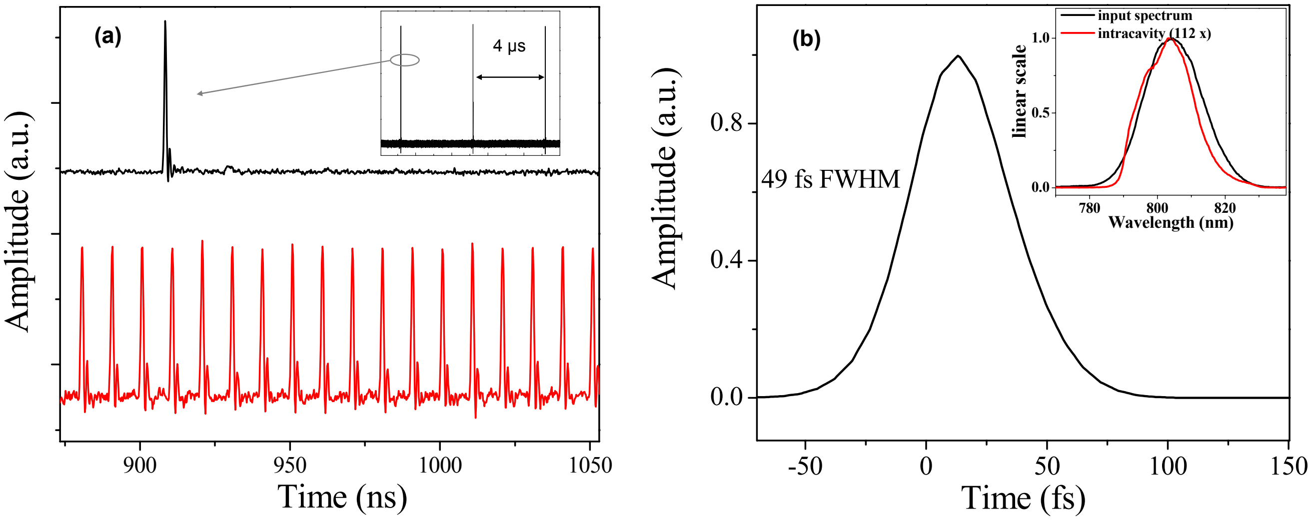

Fig. 2. (a) Intracavity pulse train viewed from cavity transmission without cavity dumping (bottom trace) and the amplified pulse train switched out by the Bragg cell (top trace). Enhancement of low energy (~0.4 nJ) pulses to > 110 times intracavity with up to 50% dumping efficiency possible. (b) Inset shows comparison of spectrum between the input and intracavity pulses. Nearly bandwidth limited 49 fs pulses are obtained after recompression for the amplified pulses.

We start with relatively low pulse peak powers in order to clearly separate linear amplification factors from nonlinear effects. Figure 2 shows the effect of intracavity enhancement and subsequent cavity dumping. The bottom trace in Fig. 2(a) shows the intracavity pulse train monitored by transmission through one of the cavity mirrors with a known transmission coefficient when the Bragg cell is inactive. With an input pulse energy of about 0.4 nJ, an intracavity amplification factor of greater than 110 is achieved. The top trace in Fig. 2(a) shows the pulse train switched out by the Bragg cell, with nearly 50% switching efficiency. We have chosen a repetition frequency of the switched pulse to be at 250 kHz (as seen in the inset of Fig. 2(a)), nearly matched to the ratio of the original pulse repetition rate over the cavity finesse. Figure 2(b) shows both time-domain and frequency-domain characterization of the pulses built up by the passive cavity. The frequency-domain data shows that the spectrum of the intracavity pulse is nearly unaltered from the input spectrum. A FROG measurement on the switched pulse yields a pulse duration of ~ 49 fs after recompression, which is nearly transform limited (time-bandwidth product ~0.41) and only slightly longer than the incident pulse duration of ~ 47 fs.

At higher pulse peak intensities, nonresonant electronic and Raman nonlinearities can distort the intracavity pulse and prevent efficient cavity buildup. Experimentally we have found that by simply stretching the pulse longer we can avoid these nonlinear effects. For the highest incident pulse energies available (>5 nJ), the 10 cm piece of SF 10 glass is not sufficient to stretch the pulse to a desirable length. Nevertheless, Fig. 3 shows a dumped pulse with an energy enhancement factor of > 50 still obtained. Meanwhile, the pulse duration has been broadened to about 90 fs, after recompressing. Because of insufficient pre-stretching of the incident pulses, the intracavity pulse spectrum can exhibit a significant spectral shift and pulse breakup can also take place. We have solid experimental evidence that in future experiments when the input pulses are sufficiently stretched we will be able to recover the results we obtained at lower energies as shown in Fig. 2. Demonstrating similar amplification results with shorter pulses (~ 20 fs) will also be explored experimentally in the near future.

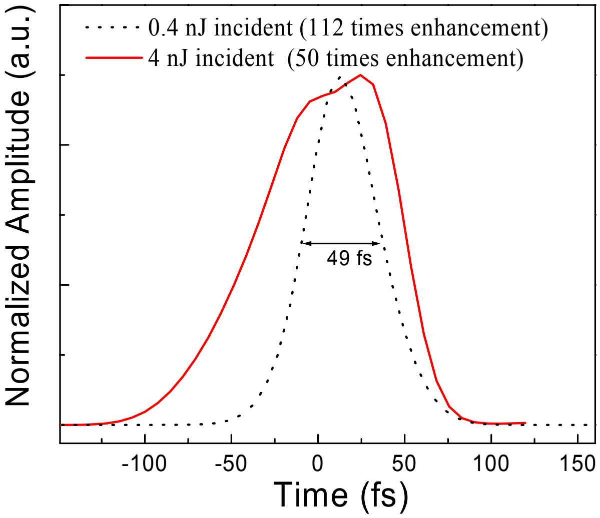

Fig. 3. Pulses switched out from the buildup cavity with different input pulse energies. Distortion due to nonlinear response of enhancement cavity transfer function at higher peak intensities results in pulse splitting and a shifts of the pulse spectrum.

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## References

1. A. M. Kowalevicz, Jr., A. T. Zare, F. X. Kärtner, J. G. Fujimoto, S. Dewald, U. Morgner, V. Scheuer, and G. Angelow, Opt. Lett. **28**, 1597 (2003).
2. A. Baltuska, Z. Wei, M. S. Pshenichnikov, D. A. Wiersma, and R. Szipöcs, Appl. Phys. B **65**, 175 (1997).
3. R. J. Jones and J. Ye, Opt. Lett. **27**, 1848 (2002).
4. R. J. Jones and J.-C. Diels, Phys. Rev. Lett. **86**, 3288 (2001).
5. R. J. Jones, I. Thomann, and J. Ye, Phys. Rev. A, Rapid Comm., in press (2004).
6. E. O. Potma, C. Evans, X. S. Xie, R. J. Jones, and J. Ye, Opt. Lett. **28**, 1835 (2003).