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Abstract: We designed and constructed a nonlinear crystal-based short pulse recirculation cavity that traps the second harmonic of an incident high power laser. This scheme aims to increase the efficiency of Compton-scattering based light sources.

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Many applications of high intensity lasers such as Compton-scattering based light sources, high-harmonics generation, laser produced plasmas and Thomson scattering are limited by low conversion efficiencies. The efficiency of nonlinear process induced by interaction of a short intense laser pulse with an optically thin medium could be increased by reusing the laser photons after each interaction. Current pulse recirculation schemes are based either on resonant cavity coupling [1, 2] or active (electro-optic) pulse switching [3, 4] into and out of the resonator.

Here, we describe an alternative efficient pulse trapping scheme based on nonlinear frequency conversion, termed recirculation injection by nonlinear gating (RING). In the simplest implementation of this technique, the incident laser pulse at the fundamental frequency enters the resonator and is efficiently frequency doubled. The resonator mirrors are dichroic, coated to transmit the (1ω) light and reflect the 2nd harmonic (see Fig. 1). The upconverted 2ω pulse becomes trapped inside the cavity. After many roundtrips, the laser pulse decays primarily due to Fresnel losses at the crystal faces and cavity mirrors. The major advantage of the outlined recirculation scheme compared to active (electro-optic or acousto-optic) pulse switching is that the pulse traverses a significantly thinner optical material. Conversion efficiency, $\eta \propto IL^2$, where I is the pulse intensity and L is the crystal thickness. A 1 mm thick BBO crystal efficiently frequency doubles pulses at incident intensities of ≈ 10 GW/cm². A typical thickness for a Pockels cell and a waveplate is ≈ 1 cm. For short, high peak power pulses, nearly an order of magnitude decrease in the length of the traversed medium reduces pulse dispersion and nonlinear phase accumulation that ultimately leads to beam break-up. Resonant cavity coupling techniques have so far been demonstrated for low peak power pulses.

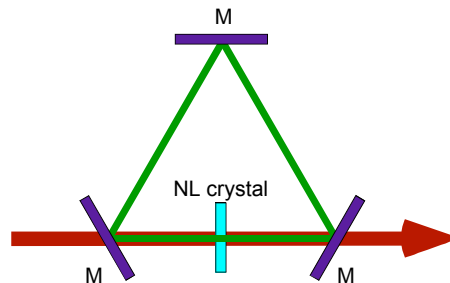


Fig. 1. RING cavity principle

We have completed a proof of principle experiment which demonstrates the RING scheme [Fig 2(a)]. The experiment was conducted at the Advanced Petawatt Concepts facility at LLNL [5]. The incident pulse was at 1053 nm, 10 Hz, chirped from its 250 fs transform limit to 1 ps, with a pulse energy of 2 mJ. The spatial profile of the incident beam was nearly gaussian in space, with a spot size of 3 mm and nearly flat-top in time. A lens telescope collimated the laser beam before the resonator. An anti-reflection (AR) coated Type I BBO crystal was 3 mm thick and achieved conversion efficiency of 25% to 2ω . The corresponding intensity at 526.5nm was 7 GW/cm². Flat 1" dichroic cavity mirrors were e-beam coated by Lattice Electro-Optics to achieve vendor specified transmission of $>98\%$ at 1053nm and reflection of $>99.7\%$ at 526.5nm. A pair

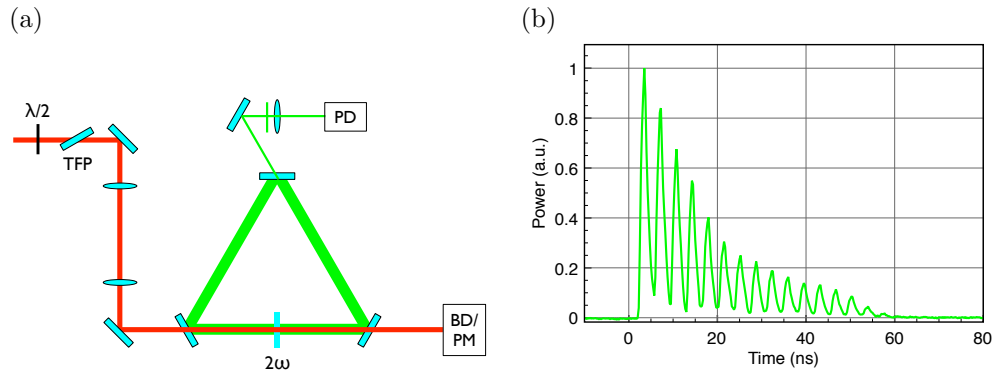


Fig. 2. (a) RING cavity experimental set-up and (b) the associated recirculating 2ω signal in the cavity vs time. The integrated energy is $5.2\times$ higher than for a single pass.

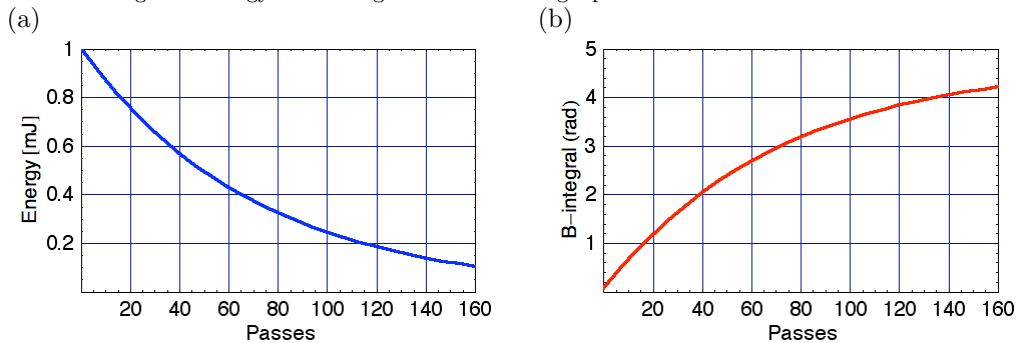


Fig. 3. Numerical modeling of 3 mirror RING cavity performance, assuming a total loss of 1.3% per roundtrip. (a) Pulse energy in the cavity vs number of roundtrips. The total predicted cavity enhancement is 71. (b) Nonlinear phase accumulation versus the number of roundtrips.

of photodiodes monitored the recirculating light by measuring the scatter off the nonlinear crystal and the leakage through one of the cavity mirrors.

The cavity ring-down signal is shown in Fig. 2(b). The scatter signal from the BBO crystal measured by the photodiode decays with each roundtrip inside the cavity. In this initial experiment, we achieved a total signal enhancement of 5.2, calculated as the ratio of the integrated energy of all the roundtrips divided by the energy in the initial 2ω pulse. Our simulations indicate that the poor AR coatings on the BBO crystal are responsible for the rapid signal decay. We estimate a total loss of 19.2% per roundtrip. Improved coatings should significantly enhance the performance of the RING cavity in our future experiments.

We simulate the expected performance of the three mirror cavity assuming a reflection of 99.7% at each mirror, transmission of 99.6% through the crystal, and crystal thickness of 1 mm. The values for linear crystal absorption and the nonlinear refractive index are estimated as 0.01 cm^{-1} and $5.5\times 10^{-16}\text{ cm}^2/\text{W}$, respectively. We assume intensity of $10\text{ GW}/\text{cm}^2$ in the initial 2ω pulse and neglect any diffraction losses. We predict cavity enhancement of 71 by integrating the energy versus roundtrips curve of Fig. 3(a). For these parameters, the nonlinear phase accumulation in the BBO crystal exceeds 3.5 rad after 100 cavity roundtrips. The pulse dispersion is relatively low, as the beam travels through a total of 10 cm of BBO crystal after 100 roundtrips.

The primary motivation behind the RING technique is the average brightness enhancement of high peak power γ -rays generated by Compton-backscattering laser photons off a relativistic electron beam. This Compton-backscattering based light source ((T-REX) is currently under construction at LLNL [8]. Specifications for the RING cavity include a focal spot of $20\text{ }\mu\text{m}$, peak intensity of $10^{14}\text{ W}/\text{cm}^2$, laser pulse duration of 10 ps, and total pulse energy of 500 mJ at 532 nm. In addition, the optical cavity must be robust, reliable, and simple to align and operate. Our final RING design of Fig. 4 meets the outlined specifications.

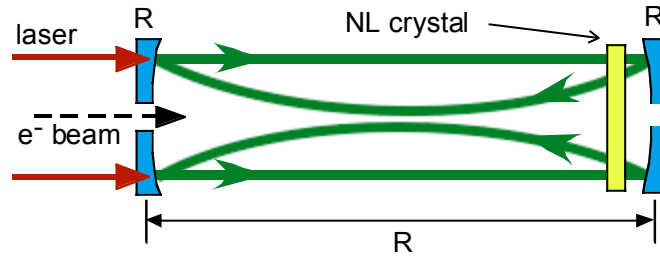


Fig. 4. RING cavity design for Compton-backscattering based light source. The entrance and exit mirrors have a hole for passage of the electron beam.

The linear RING cavity consists of two concave mirrors with identical radii of curvature and a nonlinear crystal placed near one of the mirrors where the laser intensity is lowest. The mirror spacing is equal to the sum of the focal lengths of the two mirrors. The cavity is self-imaging, meaning that the ABCD matrix for one roundtrip is $\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$. The curvature of the incident 1ω beam is adjusted to produce a collimated wavefront after the first cavity mirror. This produces a collimated 2ω pulse after the nonlinear crystal. The 2ω beam focuses when traveling from right to left and recollimates when traveling from left to right inside the cavity. The focal length of the mirrors, and hence the repetition rate of the laser pulses in the cavity will be set to an integer subharmonic of the maximum repetition rate of the arriving electron bunches (currently 2.2 GHz at the LLNL linac). The electron beam passes through a small hole (≈ 1 mm) in the entrance cavity mirror and leaves through a hole in the exit mirror. The e- beam is steered with external magnets and focuses at the laser focus. γ -ray generation occurs at the cavity focus in the propagation direction of the electron beam. This RING design can be scaled to higher incident laser powers by increasing the aperture of the cavity mirrors and the nonlinear crystal.

The nonlinear frequency conversion based beam trapping and recirculation concept can be extended to a variety of potential applications. Pulse recirculation is being considered for the proposed γ - γ collider at the International Linear Collider (ILC) [9]. Laser beam specifications at ILC are similar to our design targets. Another potential application of the RING cavity is for enhancing the conversion efficiency of frequency tripling or high harmonic generation in a gas jet placed inside the cavity.

We presented a novel pulse recirculation design suitable for trapping short high peak power pulses. RING recirculation minimizes pulse dispersion and nonlinear phase accumulation which limits the performance of active pulse switching schemes. The RING cavity should provide nearly 2 orders of magnitude improvement in average brightness of Compton-backscattering γ -ray light source currently being developed at LLNL.

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