POWER RECYCLING OF BURST-MODE LASER PULSES FOR LASER PARTICLE INTERACTIONS*

Yun Liu† and Abdurahim Rakhman
Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Abstract

A number of laser-particle interaction experiments such as the laser assisted hydrogen ion beam stripping or X-/γ-ray generations via inverse-Compton scattering involve light sources operating in a burst mode to match the temporal structure of the particle beam. To mitigate the laser power challenge, it is desirable to make the interaction inside an optical cavity to recycle the laser power. In many cases, conventional cavity locking techniques will not work since the burst normally has a very small duty factor and low repetition rate and it is impossible to generate an effective control signal.

This work reports on the development of a doubly-resonant optical cavity scheme and its locking techniques that enable a simultaneous resonance of two laser beams with different spectra and/or temporal structures. We demonstrate that such a cavity can be used to recycle burst-mode ultra-violet laser pulses with arbitrary burst lengths and repetition rates.

INTRODUCTION

In laser-particle interaction experiments such as the inverse Compton scattering based x-/γ-ray generations [1] and laser stripping of hydrogen ion beam [2], due to a very low cross-section number in the photon-particle interaction process, a very high peak power, high average power light source, often in an ultra-violet wavelength range, is required to achieve a useful efficiency. In those applications, it is desirable that lasers are operating in a burst-mode to match the temporal structure of the particle beam. Power recycling of burst-mode laser pulses would be extremely useful for such laser-particle interactions.

External optical cavities have been routinely applied to recycle the power from single-frequency lasers or mode-locked lasers which have pico-/femto-second pulses repeating at tens of MHz to GHz. Meanwhile, power enhancement of laser pulses operating at a burst mode belongs to a completely different category. Due to a very small duty factor and low repetition rate of the burst, it is impossible to generate an effective error signal within the short duration of the burst. In such a case, the conventional cavity stabilization technology will fail and a different cavity locking technology is demanded.

At SNS, we e proposed a double-resonance optical cavity (DROC) scheme and developed a robust locking scheme to realize cavity enhancement of burst mode laser pulses. In the prototype experiment, we show how a Fabry-Perot based DRPEC can be simultaneously locked to an infrared (IR) and its third-harmonic ultraviolet (UV) picosecond pulsed beams using a frequency shift technique. We have experimentally demonstrated that such a cavity can be used to enhance burst-mode UV laser pulses with arbitrary burst lengths and repetition rates.

DOUBLE-RESONANCE OPTICAL CAVITY (DROC)

Figure 1 shows an example of DROC in a Fabry-Perot scheme. The double resonance is obtained when the following condition is satisfied.

$$\mathrm{Mod}\left[\frac{\Delta L}{\min(\lambda_a,\lambda_b)}+\frac{\Delta\nu}{\min(FSR_a,FSR_b)},1\right]=0\,, \qquad (1)$$

where ΔL is the path length difference, $\Delta\nu$ is the frequency difference of the two incoming beams, *FSR* is the free-spectral range. The double resonance of a cavity to two incoming beams can be realized by one of the following two approaches.

(1) Path-length tuning approach - The in-cavity path length of one beam can be tuneable with respect to that of the other beam over a range equal to or larger than the shorter wavelength of the two beams;
(2) Frequency tuning approach - The frequency difference between two beams is tuneable up to the free-spectral range (FSR) of the cavity.

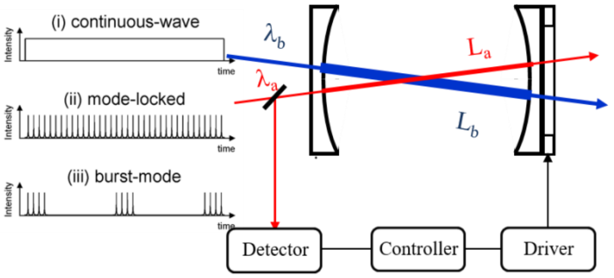

Figure 1: Conceptual diagram of DROC. A single cavity is simultaneously locked to two incoming beams with different wavelengths and operation modes.

For the path-length tuning approach, an optical dispersion element is installed inside the cavity to induce the path-length difference between two beams. A pair of N-FK5 glasses (thickness 2.75 mm) were cut at the Brewster angles (56.4° and 123.6°) to maintain very small reflectance (10^{-3} ~ 10^{-4}) at both wavelengths of the incoming beams. The Brewster windows were mounted in a temperature stabilized oven with an accuracy of 0.01°C. The cavity path length difference ΔL can be well controlled by

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* Work supported by U.S. Department of Energy under contract DE-AC05-00OR22725 and also by U.S. DOE grant DE-FG02-13ER41967.
† liuy2@ornl.gov

the glass temperature that changes both the glass length and refractive index. An example of implementation is shown in Fig. 2(a). The double resonance of the cavity to 1064 nm and 355 nm beams has been experimentally demonstrated [3] using this approach. This temperature based path-length control scheme is easy to implement and applies no change to the laser system. However, the glasses induce a certain beam loss in cavity and therefore limit the achievable cavity finesse. In addition, this approach requires the two beams at different wavelengths, which limits its application in some situations.

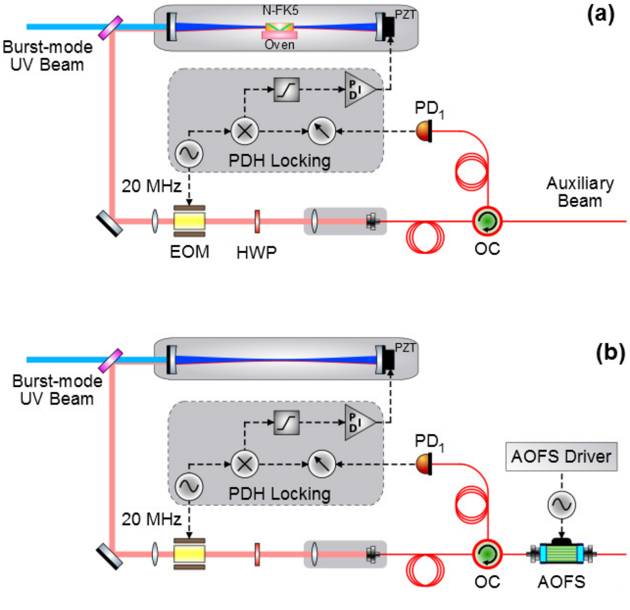

Figure 2: Two DROC locking techniques. (a) Path-length tuning using temperature control; (b) Frequency tuning using acousto-optic shifter.

The frequency tuning approach, on the other hand, is not subject to any of the above-mentioned drawbacks. One way to generate frequency difference between two beams is to use a frequency-offset optical phase-lock loop (OPLL). To tune the frequency difference up to 100 MHz at an accuracy of kHz, the OPLL requires two very stable light sources and a high bandwidth (~ GHz) locking system (including bandwidth of detection/server electronics and effects of time delay in the feedback loop), which is very challenge based on the present technology. An alternative scheme is to use acousto-optic frequency shifter (AOFS). In the traditional AOFS setup, the frequency shift always induces a change in propagation direction of the first-order diffracted beam and therefore requires realignment of the beam. However, recent fiber-pigtailed AOFS allows a large frequency tuning range with tolerable transmission losses.

EXPERIMETNAL RESULTS

Experiments of DROC have been conducted on two optical systems. Here we only describe the DROC using the frequency tuning approach. In the first experiment, both incoming beams are operating at a repetition rate of 402.5 MHz without macropulse structure. The purpose of the first experiment is to systematically study the locking condition for DROC. The optical setup of the first system is shown in Fig. 3. The master oscillator contains a CW fiber laser, a high bandwidth intensity electro-optical modulator (EOM), and a fiber based pre-amplifier [4]. The light output from the fiber laser (center wavelength 1064.5 nm with a linewidth of less than 5 kHz) is modulated by the EOM with ~ 80 ps, 402.5 MHz pulses produced from a customized radio-frequency (RF) pulse generator. The majority of the output from the master oscillator is amplified by a 40 dBm PM-YDFA, frequency tripled using a bowtie cavity enhanced second harmonic generation (SHG) and a single-pass third harmonic generation (THG) in two different Lithium Triborate (LBO) crystals. Meanwhile, a small portion of the master oscillator output passes a fiber-pigtailed two-channel Brimrose AOFS that enables a continuous frequency tuning over 220 – 370 MHz with transmission losses varying from 4 to 10 dB. The above 150 MHz frequency tuning range corresponds to 450 MHz for the UV beam, covering the FSR (402.5 MHz) of the cavity.

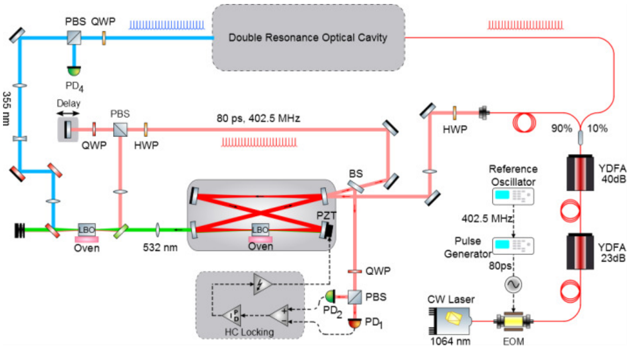

Figure 3: Experimental setup of DROC for IR and its third-harmonic beams.

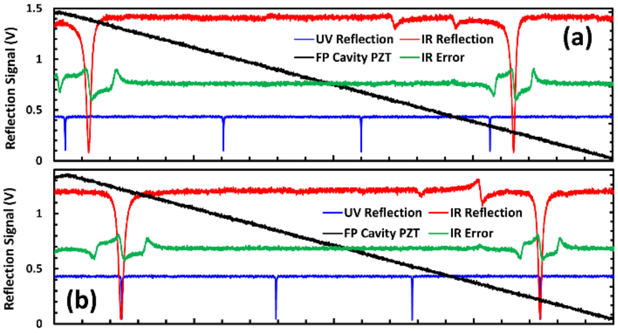

Figure 4: Light reflections and error signals measured when the cavity length is modulated. (a) IR and UV beams have different resonance frequencies and (b) double resonance is achieved by tuning the frequency offset.

Figures 4(a) and (b) show typical Fabry-Perot cavity resonance waveforms measured at different frequency offsets. The error signals in the figures are generated from the IR beam using a standard Pound-Drever-Hall (PDH) technique. The cavity finesses are about 350 for the UV beam and 70 for the IR beam in this case. Obviously in Fig. 4(a), there is an offset between the resonance frequencies of IR and UV beams. Using the AOFS to shift the IR frequency, we can align the resonance frequencies of IR and UV beams as shown in Fig. 4(b). A stable locking of the DRPEC to the beam can be realized by turning on the PDH locking circuit [5]. The maximum enhancement factor of the UV beam is about 90.

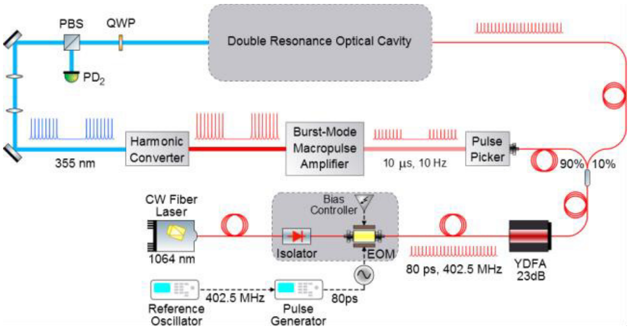

Figure 5: Experimental setup of 355 nm, 10-µs macropulse recycling in DROC.

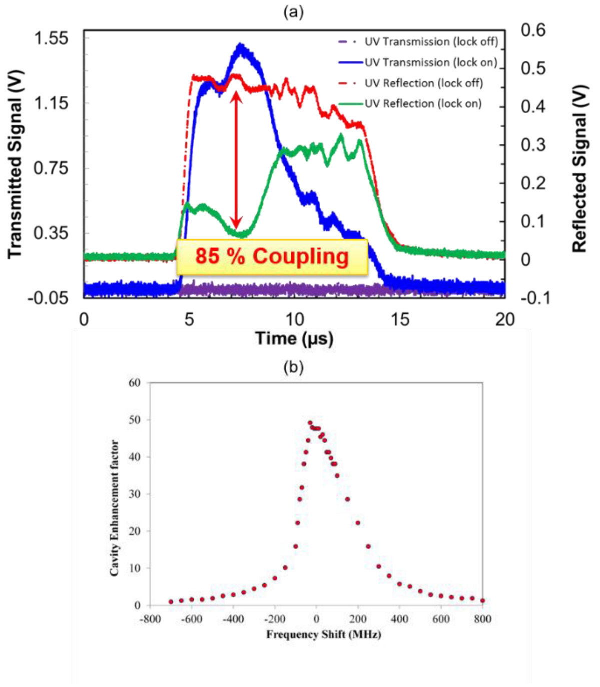

Figure 6: Experimental results of 355 nm, 10-µs macropulse amplification in DROC.

In the second experiment, burst-mode UV pulses are generated from a macro-pulse amplifier that consists of an acousto-optic modulator (AOM) based pulse picker, 6-stage Nd:YAG amplifiers, and two LBO crystals for frequency doubling and tripling [4]. The AOM pulse picker bunches the 402.5 MHz / 80 ps IR pulse train from the master oscillator into 10 us / 10 Hz macropulses with a flat top pulse shape. It is noted that the AOM also brings a 41 MHz frequency shift to the IR light. The maximum peak power of the frequency-tripled output UV pulses exceeds 1 MW. Unlike in the first experiment, we cannot find out the resonance frequency difference between IR and UV beams by directly modulating the cavity and observing the waveforms of the reflected signals such as in Fig.4. However, by scanning the frequency offset of the AOFS over the range of the cavity FSR, one can identify the necessary frequency tuning where double resonance occurs. Fig. 6(a) shows typical macropulse waveforms when the cavity is locked in a double-resonance frequency setting. Although the input UV beam has a non-ideal beam quality ($M^2 \sim 1.7$), with a proper mode matching to give the right beam waist size, an overall coupling efficiency exceeds 50% with the maximum efficiency reaches 80%. Fig. 5(b) shows the measured power enhancement factor as a function of the frequency offset applied to the AOFS. A peak enhancement factor of close to 50 has been achieved. The peak power of the build-up light inside the cavity is estimated to be about 120 kW which is limited by the damage threshold of the cavity mirror in the current experiment.

CONCLUSION

In conclusion, a doubly-resonant optical cavity that can be simultaneously locked to two laser beams with different wavelengths and temporal structures has been proposed, analyzed and demonstrated. The DROC locking technique discussed in this work can also be expanded to the locking of multiple beams to an optical cavity if the frequency tuning is implemented on the individual beams. The power enhancement of burst-mode picosecond UV laser pulses will be applied to the laser assisted hydrogen ion beam stripping experiment at the Spallation Neutron Source. The technology can also be useful for other laser particle experiments to mitigate the laser power requirement challenge.

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