STUDY ON FREQUENCY MULTIPLIER OF A PULSED LASER REPETITION USING AN OPTICAL CAVITY*

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Abstract

We have been studying a compact electron accelerator based on an S-band Cs-Te photo-cathode rf gun at Waseda University. The system is using S-band rf of 2856MHz. When a repetition of the electron bunch is integral multiple of rf, it enables a lot of electron bunch acceleration for the rf gun. The repetition of the electron bunch generated by a photo-cathode rf gun depends on the oscillating frequency of the pulsed mode-locked laser. We have been developing a mode-locked Yb-doped fiber laser based on Non-Linear Polarization Rotation (NLPR). However, its repetition is limited by the fiber length to produce NLPR. So we have started to develop the external optical cavity which is multiplier of a pulsed laser repetition. It would enable the rf gun to generate high-dose electron beam in a very short time. In this conference, we will report design of the external optical cavity to multiply the pulsed laser repetition, the experimental results of the frequency multiplying of a mode-locked Yb-doped fiber laser, and the future prospects.

INTRODUCTION

At Waseda University, a compact linear accelerator system, based on a 1.6 cell S-band Cs-Te photo-cathode rf electron gun, is applied for the various researches, such as laser Compton scattering (LCS) [1] and pulse radiolysis [2]. When a repetition of the electron bunch is integral multiple of rf, it enables a lot of electron bunch acceleration for the rf gun. The repetition of the electron bunch generated by a photo-cathode rf gun depends on the oscillating frequency of the pulsed mode-locked laser. The Yb-doped fiber laser studied as excitation pulsed laser for Cs-Te photo-cathode rf gun at Waseda University [3] has virtue of allowing high-power by Chirped Pulse Amplification (CPA), and its compactness. However it is necessary to make the repetition frequency higher in some way, because of the difficulty to get repetition rate more than about 100MHz. The repetition frequency is limited by the laser oscillation cavity length. Therefore, we have been developing an optical cavity to multiply frequency of the pulsed laser repetition.

*Work supported by Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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PRINCIPLE OF FREQUENCY MULTIPLIER USING AN OPTICAL CAVITY

In order to multiply the repetition frequency of pulsed laser by an optical cavity, there are roughly two conditions.

The first condition is that an optical cavity length matches with an integral multiple of laser half-wavelength. The condition is shown in Fig. 1.

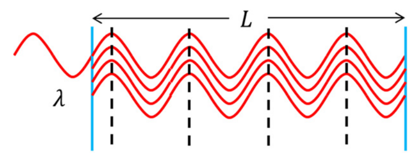

Figure 1: Schematic of storage condition of CW laser.

This is storage condition of continuous wave (CW) laser, and given by:

$$L = n\frac{\lambda}{2} \tag{1}$$

where L, λ, and n are the optical cavity length, laser wavelength and integer, respectively.

The second condition is that an optical cavity length matches with integer part of the laser's going around length. The condition is shown in Fig. 2.

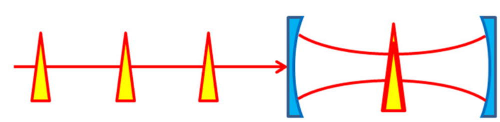

Figure 2: Schematic of overlapping of pulses.

This is overlapping of pulse, frequency multiplying, and given by:

$$L = \frac{L_{laser}}{m} = \frac{c}{mf_{rep}} \tag{2}$$

where L_{laser}, c, f_{rep}, and m are the laser oscillator cavity length, velocity of light, repetition frequency of pulsed laser and integer, respectively.

It is possible to achieve storage of pulsed laser and frequency multiplying of pulsed laser repetition by that consists of an optical cavity to satisfy the above conditions. The repetition frequency of pulsed laser passed this frequency multiplier is $f'_{rep} = mf_{rep}$ (Fig. 3).

ISBN 978-3-95450-168-7

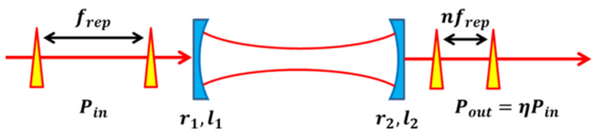

Figure 3: Schematic of a frequency multiplier.

DESIGN OF OPTIMUM OPTICAL CAVITY

At the frequency multiplying storage of pulsed laser, the key issue is frequency multiplying efficiency.

In this section, we describe about an optical cavity which is consisted of two concave mirrors for simplicity. The frequency multiplying efficiency (or the transmission of optical cavity) η is as follows:

$$\eta = \frac{(1-r_1^2-l_1)(1-r_2^2-l_2)}{(1-r_2^n r_2^n)^2} \tag{3}$$

where r_1 and r_2 are the reflectivity coefficient of two concave mirrors, l_1 and l_2 are the loss of each mirrors, n is multiple number(integer). Using this η and incident laser power P_{in}, output laser power from optical cavity P_{out} is expressed as $P_{out} = \eta P_{in}$. From Eq. (3), the frequency multiplying efficiency depends on the reflectivity coefficient and loss of optical cavity mirrors. So if we assume r_1(or r_2), there exists r_2(or r_1) which optimize η. For instance, we assume $r_1 = \sqrt{0.99}$ and n=2, the other reflectivity coefficient r_{2opt} is $r_{2opt} \simeq \sqrt{0.99}$ (assume that $l_1 = l_2 = 0$). When this condition, frequency multiplying efficiency is being optimum value, $\eta_{opt} \simeq 25.2[\%]$. Here we calculate optimum efficiency to each multiple number at $r_1 = \sqrt{0.99}$, as shown in Fig. 4.

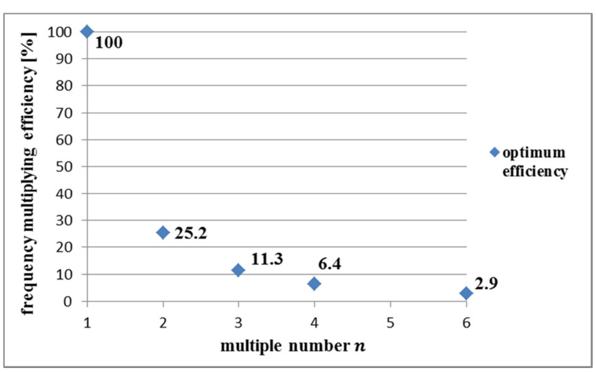

Figure 4: Calculated optimum efficiency for each multiple number.

As might be expected, $\eta_{opt} = 100[\%]$ at $n = 1$. And as multiple number increases, optimum efficiency decreases. Increasing of the multiple number n corresponds to the decreasing of the pulse accumulation in one round trip in the cavity, i.e. the pulse injected to the cavity with each n round trip. Thus the multiply efficiency is decreased. In addition, $\eta_{opt}(n = 4)$ is higher than $2 \times \eta_{opt}(n = 2)$. This fact means that fewer operations are more efficient even the same number of multiplying. When designing optical cavity, it is important to consider this optimum efficiency and use the lowest loss mirrors.

EXPERIMENTAL SETUP

The pulsed laser, which we used, is a 1030nm mode-locked Yb-doped fiber laser. It has an output power about 100mW at 1030nm with linewidth > 4.5THz(16.2nm). The repetition frequency of pulsed laser is 36.0MHz. The schematic of our Yb-doped fiber laser and pulse shape are represented in Figs. 5 and 6.

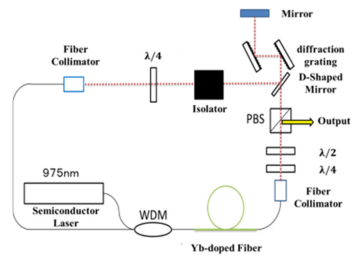

Figure 5: Pulsed laser setup.

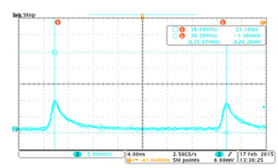

Figure 6: Pulse shape.

We designed an optical cavity to multiply repetition frequency of this pulsed laser by 4 (36.0MHz to 144MHz) in this experiment. The optical setup and picture are represented in Fig. 7, Fig. 8.

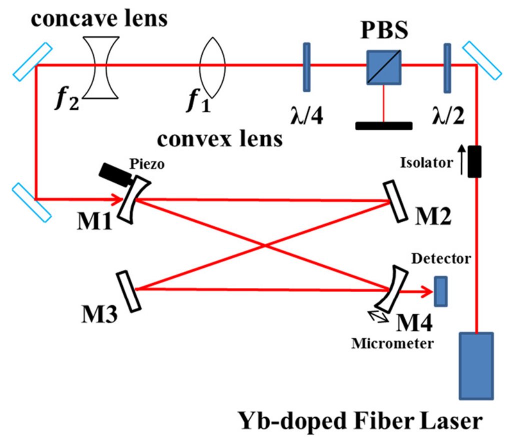

Figure 7: Optical setup.

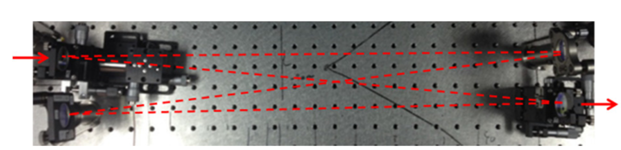

Figure 8: Photograph of the optical cavity.

The multiply cavity consist of 4 mirrors. Reflectivity coefficient of the optical cavity mirrors are $r_1 = r_4 =$

$\sqrt{0.99}$, $r_2 = r_3 = \sqrt{0.996}$, respectively. At this condition, frequency multiplying efficiency is expected to be $\eta = 3.3[\%]$ without considering mirror loss. According to circumstances, we structured an optical cavity using the mirrors are compliant YAG laser (1064nm).

RESULTS

We observed the optical cavity transmission light using the photo diode detector. The pulse shape which passed the optical cavity is represented in Fig. 9.

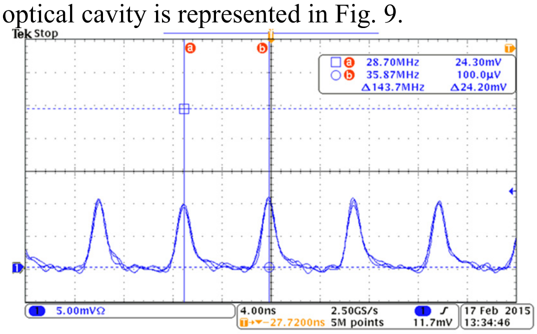

Figure 9: Multiplied pulse shape (passed cavity).

Measured repetition frequency by Fig. 9 is 144MHz. We obtained the pulsed laser which is multiplied its repetition frequency just as designed (36.0MHz to 144MHz). And frequency multiplying efficiency, which was obtained by the optical cavity transmitted pulsed laser power, was $\eta = 1[\%]$. As the expected frequency multiplying efficiency which is described above section was $\eta = 3.3[\%]$, this calculated efficiency was not include the loss of mirrors. In addition, we structured the optical cavity using the mirrors are compliant YAG laser (1064nm, Yb-doped fiber laser is 1030nm). Considering these things, the efficiency obtained by experiment was thought to be reasonable value.

To scan the optical cavity length by the piezo actuator, the resonant peaks which are called "airy function" can be obtained in the fashion. The airy function is represented in Fig. 10.

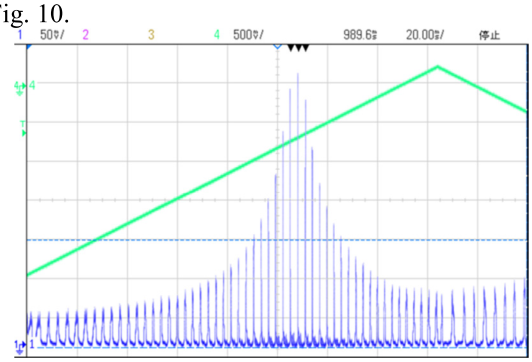

Figure 10: Airy function of the optical cavity.

The green waveform shows the voltage of the piezo actuator, which means the optical cavity length expansion. The blue waveform shows the signal from the photo diode detecting the cavity transmitted laser power. Each peak is satisfied the CW laser resonant condition. The peak which is highest power is satisfied most accurately overlapping of pulse. From this airy function, we can obtain the optical cavity finesse. This is defined as the ratio of free spectral range (FSR), and full width at half maximum (FWHM) of resonant peak (Fig 11):

$$F = \frac{FSR}{FWHM} \tag{4}$$

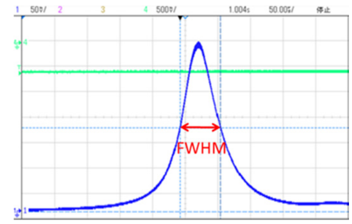

Figure 11: Resonant peak of the optical cavity.

"Finesse" is the value of representing Quality factor of the optical cavity. As the finesse is higher, the resonance of the optical cavity is sharper. The calculated finesse by the reflectivity coefficient is $F = 56$, while measured by Fig.10 was $F \simeq 50$. It is almost agreed with each other. In addition, we can calculate the linewidth of the pulsed laser from the width of this airy function (Fig. 10). As a result of calculation, it was 16nm and consistent the original pulsed laser.

CONCLUSIONS AND PROSPECTS

In this paper, we have presented the frequency multiplier of the pulsed laser repetition using the optical cavity. A pulsed laser frequency was multiplied by an optical cavity to 144MHz from 36.0MHz of infrared light pulse. We obtained a frequency multiplying efficiency of 1%, a finesse of 50, and linewidth of 16nm transmitted laser light from the optical cavity, which are consistent values as we expected.

In near future, we plan to structure a frequency multiplier of a 119MHz mode-locked Yb-doped fiber laser synchronizing S-band rf of 2856MHz of Cs-Te photo-cathode rf gun. As optical cavity mirrors, we plan to use optimum designed low loss mirrors and structure an optimum optical cavity, and demonstrate an optimum multiply efficiencies.

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ISBN 978-3-95450-168-7