Generation of 1.8 W Continuous Green Laser at 532 nm by Passively Resonant Enhancement Technique in a Fiber Laser

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ABSTRACT- In this paper, design and fabrication of an internal resonant enhanced frequency doubling of the continuous-wave ytterbium-doped fiber laser at 1064nm using a Fabry-Perot bow tie cavity inside the fiber laser cavity is presented. The 3.5W power coupled into the enhancement cavity is amplified to 163W by the intracavity passive locking technique. By placing an LBO crystal within this resonant enhancement cavity, conversion efficiency of the second harmonic generation of the laser in continuous regime is increased from 0.023% to 51.42% (i.e. about 2200 times) which results to generation of 1.8W light at 532nm.

KEYWORDS: Internally resonant enhancement, Second harmonic generation, Bow tie Fabry-Perot cavity, fiber laser.

I. INTRODUCTION

High-power continuous wave lasers in the visible spectrum have many applications in the flow cytometry [1], underwater optical communication [2], optical bio-imaging [3] and optical pumping of lasers [4]. There are only a few laser sources which offer such wavelengths. The common approach to achieve laser sources in the visible region relies on the frequency doubling of the near infrared (NIR) wavelengths. However, in the continuous-wave regime, the conversion efficiency of second harmonic generation by using nonlinear materials is low and, consequently, high-power NIR lasers are required to generate desired level of power of the converted visible light. However, such power scaling requirement is restricted because of different problems such as thermal effects.

Development of the high-power fiber lasers, especially in the NIR region, offers a promising solution for frequency doubling of the beam to acquire high-power visible sources[5]–[8]. In these systems, efficiency of the second harmonic generation is significantly increased by a resonantly enhanced beam that is produced in a cavity which contains a nonlinear crystal. In 1966, Ashkin *et al*. [9] enhanced the SHG power by locking a He-Ne laser to an enhancement cavity that contains a KDP crystal. In 1991, Yang *et al*. [10] generated 6.5W of green light at 532nm from 18W of 1064nm light using actively locked external cavity with 36% of efficiency. However, the external enhancement cavities required sophisticated electronic feedback loop and also a very narrow-bandwidth fiber laser (about 1KHz ~ 30 MHz) [11]. To overcome the restrictions of active locking method, Cieslak *et al*. [12] described a new approach based on an internally resonant enhancement of frequency doubling by inserting a free space bow-tie cavity inside a fiber laser cavity and passively locking of two cavities. The same method was used to obtain 450 nm light from the 900 nm emission in the Nd-doped fiber laser [13].

In this paper, we, first, report on design and experimental realization of a fiber laser based on a 20/400 double cladding ytterbium-doped fiber as a gain medium that is optimized to well operate with an internal enhancement cavity. Then, a bow tie enhancement cavity containing an LBO crystal is placed inside the fiber laser cavity that results to multiple amplification of the circulating light at 1064 nm inside the enhancement cavity and strong increase of the efficiency of the green light generation at 532 nm.

II. EXPERIMENTAL SETUP

Schematic of the experimental setup is shown in the Fig 1. The main fiber laser cavity consists of two high reflective mirrors at 1064 nm and 20 m length of the 20/400 double cladding ytterbium-doped fiber as gain medium which is coiled up to a diameter of 12 cm to suppress the higher order transverse modes and the optimum operation in the fundamental mode. The optimum coiling radius is numerically calculated based on the fact that a properly coiled fiber has higher bending losses for higher order modes as compared to the fundamental mode. The 20-meter length of fiber also provides stable performance of the cavity with high fineness. The optical pumping of the gain medium is performed by two fiber-coupled diode lasers with output power of up to 35W and the wavelength of 976 nm. Both fiber ends are angle cut at 8° to eliminate the back reflections. Since the gain fiber does not maintain the light polarization, a quarter wave plate and a Glan-Taylor polarizer are inserted into the main cavity to partially compensate depolarization within the fiber and to properly adjust the beam polarization state inside LBO crystal.

The internal enhancement cavity with bow-tie geometry consists of plane input and output mirrors of M1 and M2, respectively, which are separated by distance of 150 mm, two spherical concave mirrors of M3 and M4, and nonlinear crystal of LBO cut for type I (ooe) noncritical phase matching placed at the focus of the curved mirrors. The optimum transmissions of the input and output mirrors of M1 and M2 are calculated at the next section. Both curved mirrors have radius of curvature of 100 mm with reflectivity of 99.8% at 1064 nm and transmittance of 95% at 532 nm. The LBO crystal is located in the middle of the M3 and M4 mirrors. Two lenses of L2 and L3 are used to spatially match the fundamental transverse mode of the fiber laser with the TEM00 mode of the enhancement cavity. The fiber laser forced to operate at 1064 nm wavelength by inserting a band-pass filter with the FWHM of 10 nm.

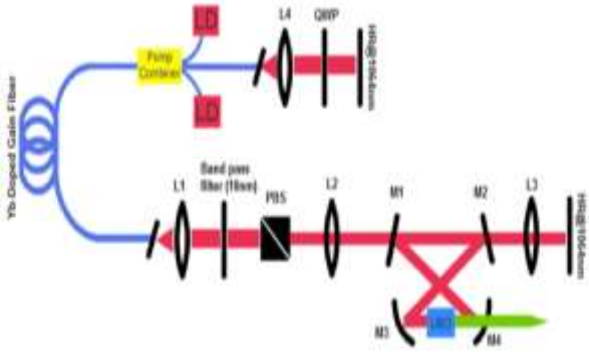

Fig. 1. The schematic view of the experimental setup of an internal resonantly enhancement of SHG inside a fiber laser.

Unidirectional conversion and the lack of unwanted feedback lights from M1 and M2 mirrors into the fiber laser are resulted by bow tie geometry of the enhancement cavity.

III. THEORETICAL ANALYSIS

External or internal enhancement cavities can be used to enhance power of the SHG beam by actively or passively locking of such cavities to the main laser cavity. In a bow-tie geometry of the enhancement cavity with the schematic shown in Fig 1, the enhanced circulating power for different input powers can be calculated as [13]:

$$P_c = \frac{p_i\left(1-r_1^2\right)}{\left(1-r_1 r_2 r_{HR}^2\sqrt{\gamma_{SHG}P_c\left(1-\alpha\right)}\right)^2} \tag{1}$$

Where, P_c is the circulating power, r_1 and r_2 are the reflectivity amplitudes of mirrors M1 and M2, respectively. α represents the total intracavity losses, r_{HR} is the reflectivity of the curved mirrors, and γ_{SHG} is the single pass efficiency of the nonlinear crystal. The maximum amount of circulating power is acquired when the transmission of the input coupler mirror is equal to the total losses, i.e.:

$$r_1 = r_2 r_{HR}^2 \sqrt{(1-\alpha)(1-\gamma_{SHG} P_c)} \quad (2)$$

Under this condition, the circulating power reaches its maximum value which is given by:

$$P_c = \frac{P_i}{T_1} \quad (1)$$

Here, $T_1 = 1 - r_1^2$.

One can prove that the minimum length of the fiber laser cavity for stable operation of the enhancement cavity inside the main laser cavity is given by [14]:

$$L_{\min} = Fd \quad (4)$$

In this equation, $L_{\min}$ is the minimum required round trip length of the fiber laser cavity for passive locking, F is the finesse of the enhancement cavity, and, d is the round-trip length in the enhancement cavity. According to this equation, the round-trip length of the main cavity should be at least 20 meters.

In this case, at least one of the longitudinal modes of the fiber laser will always be placed at the transmission's peaks of the enhancement cavity, and hence, two cavities can passively lock together. For regular operation of the system, the stability of the bow-tie enhancement cavity should first be evaluated. To do that, the ABCD matrix equations for enhancement cavity are solved by considering the experimental limitation of the angle of incidence of the mirrors, and, operation of the cavity at the middle of the stability range. Fig 2 shows the variation of the waist radius of the fundamental mode along the cavity. In the middle of the two plane mirrors the waist radius of the beam is calculated 223 microns in tangential plane and 263 microns in sagittal plane. Also, the waist radius at the middle of the nonlinear crystal is calculated wt=48.48 microns in the tangential plane and ws=50.46 microns in sagittal plane (Fig. 3).

The ratio of ws/wt, which is a measure of the astigmatism within the crystal, is equal to 96% which indicates that the astigmatism is well compensated in the middle of the nonlinear crystal.

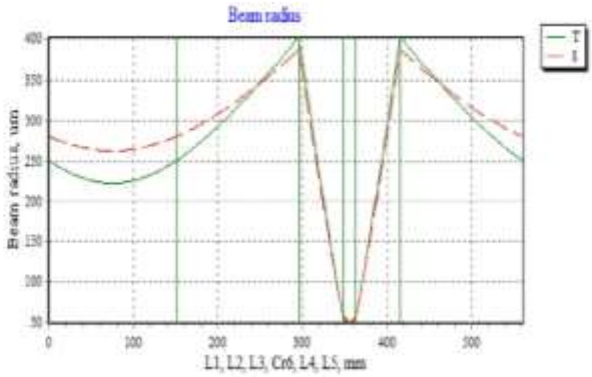

Fig. 2. Beam radius along the designed enhancement cavity

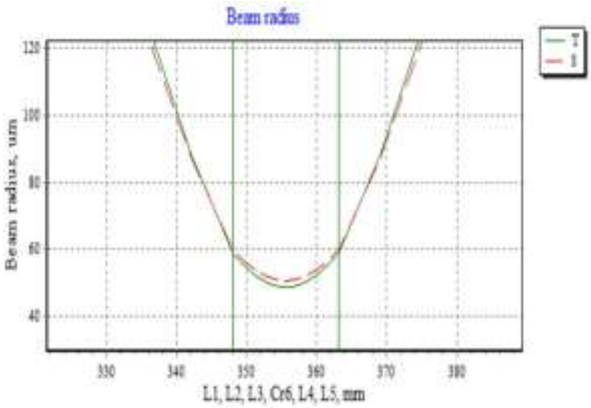

Fig. 3. Beam radius along LBO crystal.

In order to attain maximum circulating power in the enhancement cavity, the transmission of the input coupler mirror should be equal to the total losses inside the cavity. On the other hand, a sufficient feedback power on the backward direction is required for the optimal performance of the fiber laser. Therefore, Eq. (2) should be solved for different values of the reflectivity of the output coupler mirror (M2) and for certain amount of reflectivity of the input coupler mirror (M1) to achieve the maximum circulating power. Fig 4 shows variation of the circulating power as well as the amount of the feedback IR power which inject into the fiber in the backward direction versus the reflectivity of M1 mirror.

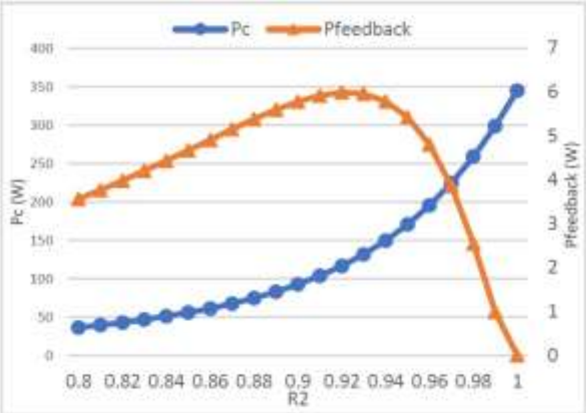

Fig. 4. Evolution of circulating power respect to different reflectivity amounts of M2.

The incident power on M1 (the power in the main cavity) is assumed equal to 15W and the total losses of the cavity is equal to α=0.0015. Also, the reflectivity of mirrors of M3 and M4 assumed to be 99.8% for 1064 nm and the reflectivity of the input coupler mirror is set to 95.5%. As shown in the Fig 4, for M2 reflectivity of 98.5%, a high circulating power can be obtained while a sufficient amount of feedback power on the backward direction of about 1.5 W is also provided.

Moreover, the amounts of circulating power versus different reflectivities of M1 for given M2 reflectivity of 98.5% are depicted in Fig 5.

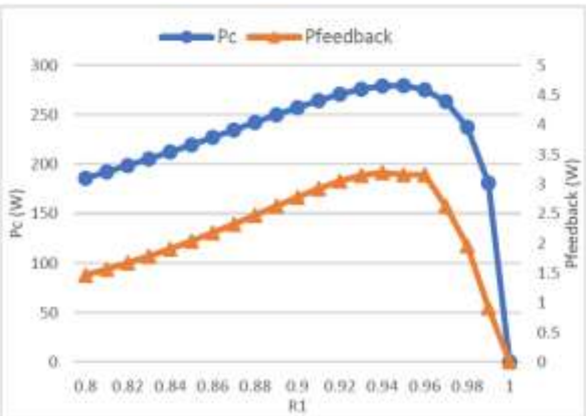

Fig. 5. Evolution of circulating power respect to different amounts of M1.

As shown in the Fig 5, maximum circulating power is obtained for the M1 reflectivity of 95.5%.

Therefore, the optimum transmissions of 4.5% and 1.5 % for the input and output mirrors of M1 and M2 should be used for the experimental setup shown in Fig 1.

IV. Experimental Results

In the following, the measured values for the circulating power inside the enhancement cavity in terms of the incident powers on M1 mirror are compared with the calculated theoretical values. By measuring the incident and the reflected powers for M1 mirror the coupled power into the enhancement cavity can be measured. For this purpose, a thin glass plate with a low reflection is placed before M1 mirror at 45^{o} angle relative to the optical axis to sample the circulating power inside the main laser cavity. Fig 6 illustrates the theoretical and measured experimental values of the circulating power with respect to the incident powers. Fig 7, also, shows the measured powers coupled into the enhancement cavity and the SHG powers versus different amounts of the incident powers on M1.

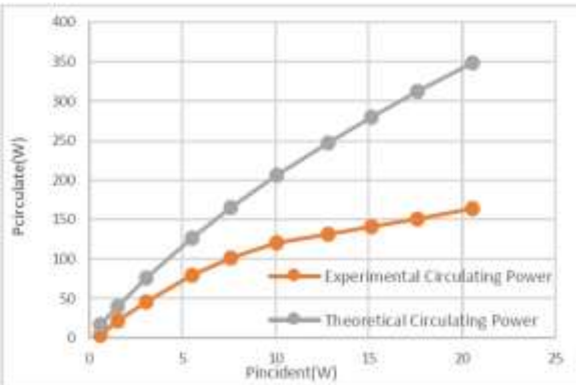

Fig. 6. Theoretical and measured experimental values of circulating power inside the enhancement cavity.

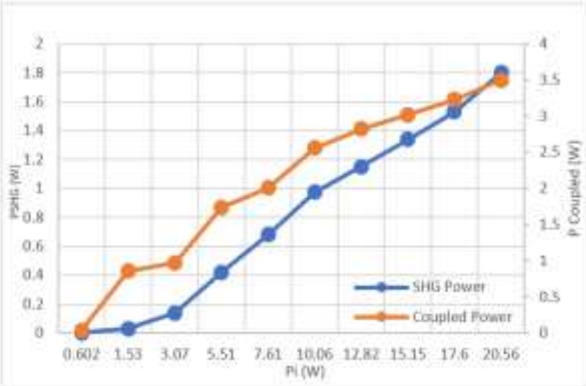

Fig. 7. Coupled power and SHG power respect to incident power on M1.

As observed, for the incident power of 20.56W on the M1 mirror, just 3.5 W of light at 1064 nm is injected into the enhancement cavity. However, from this amount of coupled NIR light, 1.8 W of the green light at 532 nm is extracted because of the power amplification in the Fabry-Perot cavity. Although, the conversion efficiency of the LBO crystal is calculated to be 0.023% for a radius of 49 microns in the middle of the crystal and for input power of 3.5W, but, by placing the LBO crystal inside the enhancement cavity, the conversion efficiency rises to 51.42% respect to the coupled power into the cavity. Therefore, the conversion efficiency of the LBO crystal is increased about 2200 times because of the resonant enhancement of the NIR light.

Deviation the experimental values from theoretical values, observed in the Fig 6, is expected for several reasons. One of the most important reasons is that the electromagnetic field which circulates inside the enhancement cavity does not have the exact polarization required for the x-cut LBO crystal , so that a portion of the circulating light couldn't convert to the green light. Therefore, this portion is not considered in measuring of the circulating power. Moreover, the imprefect spatial mode matching can impose a huge amount of losses to the circulating light.

For above results, the LBO crystal is stabilized at the oven tempearature of about 147° C, for which the maximum SHG power can be extracted from the crystal according to the experimental diagram of Fig 8.

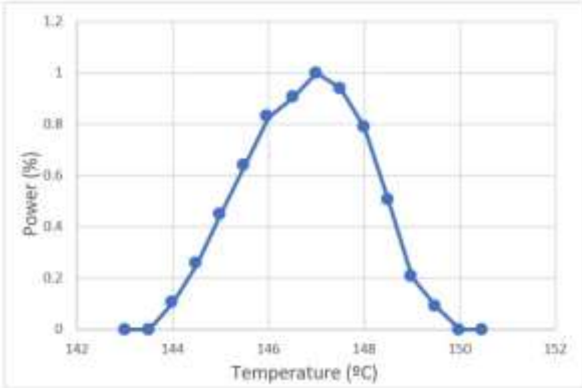

Fig. 8. Phase matching diagram of the noncritical phase matched, 15mm LBO crystal.

The measurement of the output spectrum shows the central wavelength of the green light is equal to 532.7 nm. It's indicated that the main laser cavity operates at the central wavelength of 1065.52nm.

As mentioned at the theoretical analysis section, we tried to eliminate the astigmatism at the LBO crystal in the design of the enhancement cavity. Fig 9 illustrates a picture of far field profile of the generated green light without any significant astigmatism.

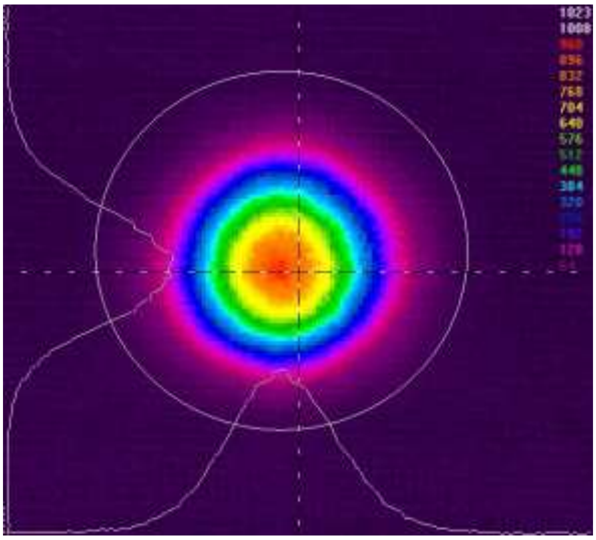

Fig. 9. Far field profile of generated 532 nm lights.

V. CONCLUSION

Consequently, by optimally designing and placing a bow-tie enhancement cavity inside a CW fiber laser and by the intracavity passive locking method, the conversion efficiency of the NIR light to the green light was increased about 2200 times and 1.8 W power of the green light at the central wavelength of 532.76 nm was resulted.

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