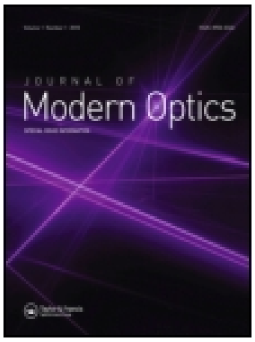

Journal of Modern Optics

ISSN: 0950-0340 (Print) 1362-3044 (Online) Journal homepage: http://tandfonline.com/loi/tmop20

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To cite this article: Chunting Wu, Fei Chen, Tongyu Dai & Youlun Ju (2015) Theoretical and experimental investigations of injection-locked signal extraction of Tm:YAG laser, Journal of Modern Optics, 62:19, 1535-1545, DOI: 10.1080/09500340.2015.1049232

To link to this article: http://dx.doi.org/10.1080/09500340.2015.1049232

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Journal of Modern Optics, 2015
Vol. 62, No. 19, 1535–1545, http://dx.doi.org/10.1080/09500340.2015.1049232

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Theoretical and experimental investigations of injection-locked signal extraction of Tm:YAG laser

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(*Received 2 February 2015; accepted 28 April 2015*)

Injection-seeded is an effective method to obtain high-power pulsed laser with pure spectrum, which is useful to be the laser source of a coherent Doppler LIDAR or a differential absorption LIDAR. In order to achieve the useful injection-locked signal, mode matching between master laser and slave laser is necessary. In this paper, various factors influencing on the extraction of injection-locked signal are analyzed theoretically. Then, experiments on an injection-seeded Tm:YAG laser are carried on, and injection-locked signal is extracted successfully. Moreover, an injection-seeded Tm:YAG laser is achieved, with pulsed single-frequency at 2013 nm, output energy of 3.16 mJ, and pulse width of 238.7 ns, at a repetition rate of 100 Hz.

Keywords: diode-pumped lasers; Tm laser; Injection-locked signal extraction

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1. Introduction

Injection-seeded is an effective method to achieve high-power pulsed laser with pure spectrum, which is useful to be the source of coherent Doppler LIDAR and differential absorption LIDAR [1–3]. In recent years, some results about injection-seeded laser have been demonstrated. In 1998, a flash-lamp-pumping, injection-seeded, Q-switched 1.552-μm Er:glass laser was reported by McGrath et al. [4]. In 2008, an injection-seeded Tm, Ho: GdVO4 laser at 77 K was reported by Wang. The Q-switched output energy of 2 mJ at 20 Hz with a pulse width of 170 ns was obtained [5]. In 2011, an injection-seeded Tm:YAG laser was reported by our group, and nearly transform-limited single-frequency pulsed 2013-nm laser with output energy of 2.0 mJ and pulse width of 356.2 ns was achieved at 15 Hz [6]. In 2011, a single-frequency Q-switched Tm:YAG laser, with pulse energy, pulse width, and repetition rate of 2.38 mJ, 308 ns, and 100 Hz was reported by Zhang et al. [7]. In 2013, an injection-seeded Q-switch Ho:YAP laser, with pulse width of 151 ns at 100 Hz was demonstrated by Dai et al. [8].

Injection-seeded laser system is mainly consisting of a master laser (seed laser), a slave laser (power laser), and a coupling system. The coupling system, which is an indispensable link, is used to extract injection-locked signal and to realize stable injection-locked laser output. The injection-locked signal extraction is influenced by the mode-matching between the master laser and slave laser. However, little study on the injection-locked signal is carried out.

In this paper, detailed study on injection-locked signal extraction is carried out, including the horizontal mode matching and the vertical mode matching between the master laser and slave laser. The method for improving the mode-matching has been analyzed and designed. Experimentally, the effective injection-locked signal of Tm:YAG laser has been extracted. At last, the experiment of injection-locked Tm:YAG laser is carried out successfully and the output characteristics have been improved because of the works mentioned above.

2. Theoretical analysis

Injection-locked signal extraction is influenced by the mode-matching (horizontal and vertical patterns) between the master laser and slave laser. Theoretically, the horizontal mode matching and the vertical mode matching will be discussed.

2.1. *Horizontal mode matching*

When the fundamental transverse mode of master laser is injected into the slave laser, the whole power of the master laser should be coupled to the fundamental mode of the slave laser. However, the power of the master laser is always coupling to the higher order modes of the slave laser, which means the transmission loss increases.

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The power coupling coefficient between the fundamental mode of master and slave laser will be decreased. It means that the power of the seed laser cannot be fully utilized.

Supposed that the master laser is fundamental transverse mode and the slave laser cavity is stable, the master and slave laser can be processed as Gaussian beam [9,10].

The mode coupling coefficients C_0 can be obtained from formula (1) by the integral of amplitude of electric field for the plane (xoy).

$$C_0 = \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E_1^* E_2 \mathrm{d}x\mathrm{d}y}{\left[\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E_1^* E_1 \mathrm{d}x\mathrm{d}y \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E_2^* E_2 \mathrm{d}x\mathrm{d}y\right]^{1/2}} \quad (1)$$

where E_i is the optical field of i-beam ($i = 1, 2$). The cylindrical coordinates of Gaussian beam E_1 could be expressed as formula (2).

$$E_1 \propto \left(\frac{2}{\pi\omega_1^2}\right)^{1/2} \exp\left(-\frac{\rho^2}{\omega_1^2} - \frac{jk_1\rho^2}{2R_1} - jkz\right) \quad (2)$$

where ω_1 is the beam radius; k_1 is the wave vector; and R_1 is the radius of curvature of the wavefront. ω_1 and R_1 are associated with the position (z) on the propagation direction, as shown in formulas (3) and (4).

$$\omega_1^2 = \omega_{10}^2 + \lambda^2(z - z_1)^2/\pi^2\omega_{10}^2 \quad (3)$$

$$R_1 = (z - z_1) + \pi^2\omega_{10}^4/\lambda^2(z - z_1) \quad (4)$$

Mode-matching between master laser and slave laser is shown in Figure 1. The main influencing factors of mode-matching are consisting of different radii of two Gaussian beams ($\Delta\omega$), different longitudinal waist positions of two Gaussian beams (Δz), lateral-position deviation of two Gaussian beams (Δx), different radii on the orthogonal directions of two Gaussian beams ($\omega x \neq \omega y$), and different spread directions of two Gaussian beams ($\Delta\theta$).

2.1.1. *Beam radius*

Suppose that the vertical and horizontal positions of two Gaussian beam waists are coincident, the beam radius coupling coefficient (C_ω) can be represented as formula (5) under cylindrical coordinate. Then, the integral can be expressed as formula (6).

$$C_\omega = \frac{2}{\pi\omega_{10}\omega_{20}} \int_0^{2\pi}\int_0^{\infty} \exp\left(-\frac{\rho^2}{\omega_{10}^2} - \frac{\rho^2}{\omega_{20}^2}\right)\rho\,\mathrm{d}\rho\,\mathrm{d}\varphi \quad (5)$$

$$C_\omega = \frac{2\omega_{10}\omega_{20}}{\omega_{10}^2 + \omega_{20}^2} \quad (6)$$

As it is known, radius of slave laser (ω_{20}) is determined when the resonator is designed. Then, the optical transformation of the seed laser injected into the slave laser resonator is certain. The transformed beam waist radius of the injected seed laser is denoted as ω_{10}.

As shown in Figure 2, for a certain ω_{20}, C_ω changes dramatically when $\omega_{10} < \omega_{20}$; when $\omega_{10} = \omega_{20}$, $C_\omega = 1$, then as ω_{10} increases, C_ω decreases gradually, but slowly. Therefore, when the mode-matching is designed, the injected beam waist should be similar or slightly larger than the beam waist of slave laser. In addition, the larger the ω_{20} is, the slower the C_ω changes with ω_{10}. It means that the ω_{20} should be appropriate when the resonator is designed to be convenient for mode-matching.

2.1.2. *Different longitudinal positions, but the same lateral position and direction of propagation*

The coupling coefficient of the longitudinal position of two beams (C_z) can be expressed as formula (7).

$$C_z = \frac{2}{\pi\omega_{10}\omega_{20}} \int_0^{2\pi}\int_0^{\infty} \exp\left(-\frac{\rho^2}{\omega_{10}^2} - \frac{\rho^2}{\omega_{20}^2} - \frac{j\pi\rho^2}{\lambda R_2}\right)\rho\,\mathrm{d}\rho\,\mathrm{d}\varphi \quad (7)$$

The integral result of formula (7) is shown in formula (8).

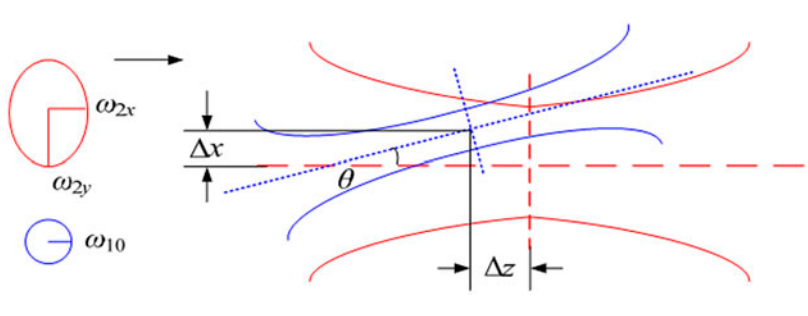

Figure 1. Coupling factors between master laser and slave laser. (The color version of this figure is included in the online version of the journal.)

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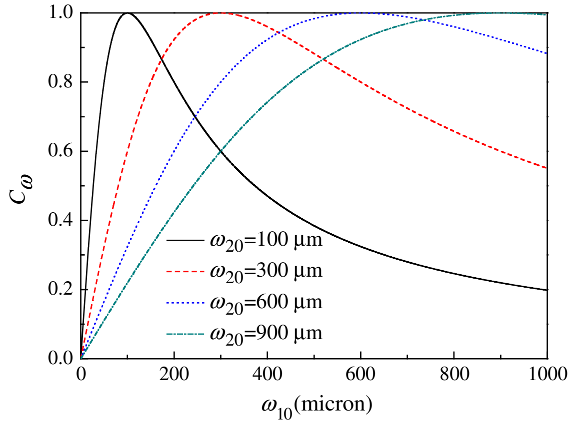

Figure 2. Coupling coefficient vs. waist radius. (The color version of this figure is included in the online version of the journal.)

$$C_z = \frac{2\omega_{10}\omega_2}{\omega_{10}^2+\omega_2^2}\left[1-\frac{j\pi}{\lambda}\frac{\omega_{10}^2\omega_2^2}{\omega_{10}^2+\omega_2^2}\frac{(z_1-z_2)}{(\pi\omega_{20}^2/\lambda^2)^2+(z_1-z_2)^2}\right]^{-1} \tag{8}$$

Supposed that the radius of two Gaussian beams is equal, as shown in formula (9).

$$\omega_{10}^2 = \omega_2^2 = \omega_{20}^2\left[1+\left(\frac{\lambda(z_1-z_2)}{\pi\omega_{20}^2}\right)^2\right] \tag{9}$$

Then, the coupling coefficient of the longitudinal position (C_z) can be expressed as formula (10).

$$|C_z| = \left[1+\left(\frac{\lambda(z_1-z_2)}{2\pi\omega_{10}^2}\right)^2\right]^{-1/2} \tag{10}$$

Formula (10) indicates that the longitudinal position of the coupling coefficient (C_z) is related with the beam radius, the position of the beam waist, and the wavelength. For Tm:YAG crystal used in the experiments, the output wavelength is 2.01 μm. The longitudinal deviation from no offset to 50 mm is shown in Figure 3. The effect of deviation of the longitudinal position to the coupling is relatively small. For example, when $\omega_{20} = 200$ μm, even if the deviation is 50 mm, C_z is still larger than 92.5%. And the greater the ω_{20} is, the smaller the influence of the deviation of the longitudinal position to the coupling efficiency.

2.1.3. *Different lateral positions, but the same propagation direction and the longitudinal position*

The coupling coefficient of the lateral position (C_X) is determined by the formula (11).

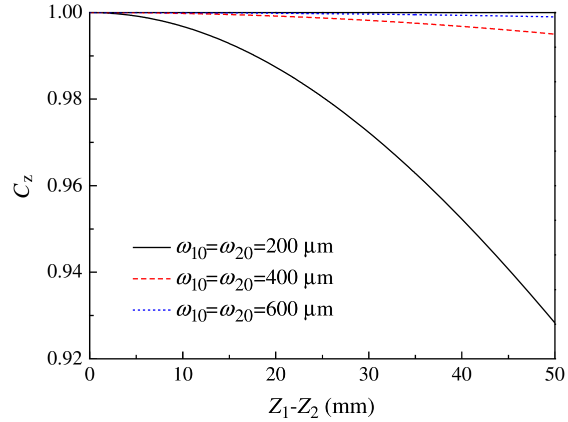

Figure 3. Coupling coefficient vs. longitudinal position with different waist radii. (The color version of this figure is included in the online version of the journal.)

$$C_X = \int_{\infty}^{\infty}\int_{\infty}^{\infty}\left(\frac{4}{\pi^2\omega_{10}^2\omega_{20}^2}\right)^{1/2}\times\exp\left[-\frac{x^2+y^2}{\omega_{10}^2}\frac{(x+\Delta x)^2+y^2}{\omega_{20}^2}\right]\mathrm{d}x\mathrm{d}y \tag{11}$$

where Δx is the lateral displacement from injected seed laser to the optical axis of slave laser. Suppose the beam is circularly symmetric, the integration result of formula (11) can be expressed as formula (12).

$$C_X = \frac{2\omega_{10}\omega_{20}}{\omega_{10}^2+\omega_{20}^2}^{1/2}\exp\left(-\frac{\Delta x^2}{\omega_{10}^2+\omega_{20}^2}\right) \tag{12}$$

Suppose $\omega_{20} = \omega_{10}$, then Δx can be simplified to formula (13).

$$C_X = \exp\left(-\frac{\Delta x^2}{2\omega_{10}^2}\right) \tag{13}$$

As shown in Figure 4, assuming $\omega_{20} = 0.6$ mm, if $\Delta x = 0.5$ mm, then C_X is calculated to be 70.7%. If $\Delta x = 1$ mm, then C_X is only 24.9%. While assuming

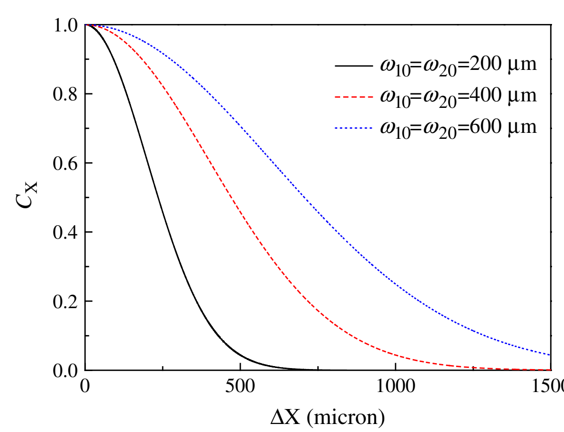

Figure 4. Coupling coefficient vs. radial position with different waist radii. (The color version of this figure is included in the online version of the journal.)

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ω_{20} = 0.2 mm, if Δx = 0.5 mm, then C_X is calculated to be 4.4%. If Δx = 1 mm, then C_X is nearly zero. Therefore, for effective coupling, it is very important to adjust the injection of seed laser. Greater ω_{20} is easy to decrease the impact of this lateral displacement. Therefore, it is appropriate to increase the value ω_{20} as designing the resonator of slave laser. Meanwhile, this lateral displacement should be avoided.

2.1.4. The same longitudinal and lateral position, the same propagation direction, but different beam radii in the orthogonal direction

For ring laser oscillator with curved mirror, the astigmatism cannot be avoided. The astigmatism coupling coefficient (C_A) is expressed as formula (14).

$$C_A = 2\sqrt{\frac{\omega_{10}^2\omega_{2x}\omega_{2y}}{(\omega_{10}^2+\omega_{2x}^2)(\omega_{10}^2+\omega_{2y}^2)}} \quad (14)$$

In order to optimize the coupling of elliptical beam, $\omega_{2y} = r\omega_{2x}$ can be supposed. Then, formula (14) might be transformed to formula (15).

$$C_A = 2\sqrt{\frac{\omega_{10}^2\omega_{2x}^2 r}{(\omega_{10}^2+\omega_{2x}^2)(\omega_{10}^2+\omega_{2x}^2 r^2)}} \quad (15)$$

Optimizing coupling can be realized by varying the beam radius (ω_{2x}), as shown in formulas (16) and (17).

$$\omega_{2x} = \omega_{10} r^{-1/2} \quad (16)$$

$$\omega_{2y} = \omega_{10} r^{1/2} \quad (17)$$

Then, C_A can be expressed as formula (18).

$$C_A = \frac{2r^{1/2}}{1+r} \quad (18)$$

C_A is only relative with the elliptical beam radius ratio r. As shown in Figure 5, when the radius of the master laser is equal to the radius of the slave laser, and the beams are closer to circularly symmetric, C_A is nearly 1.

Whether asymmetric of the injected seed laser or the existence of astigmatism in slave laser, C_A is dropped. It will influence on the mode-matching and injection-locked signal extraction. The M^2 of the seed laser should be good. And the asymmetry of seed-beam should be amended by a coupling system. As the slave laser, minimal astigmatism might be required, although multiple curved mirrors are used in the cavity.

2.1.5. Different propagation directions, but the same beam waist radius and position in the longitudinal and transverse directions

The coordinate conversion process is needed with different propagation directions, the same beam radius, and position in the longitudinal and transverse directions. The angle (θ) is an angle between the directions of propagation in the x_z plane. The relationship of coordinate conversion could be represented as formula (19).

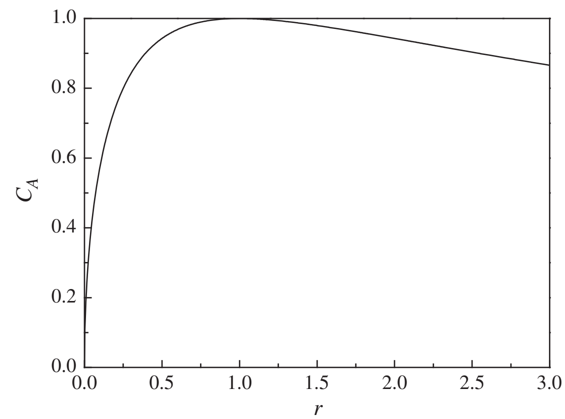

Figure 5. Astigmatism coupling coefficient vs. beam radius.

$$\begin{cases} x \to x\cos\theta - z\sin\theta \\ z \to x\sin\theta + z\cos\theta \end{cases} \quad (19)$$

When z = 0, E_2 is converted into formula (20).

$$E_2 \propto \left(\frac{2}{\pi\omega_{20}^2}\right)^{1/2} \exp\left[-jkx\sin\theta - \frac{x^2\cos^2\theta + y^2}{\omega_{20}^2}\right] \quad (20)$$

When the wave vector is equal to $2\pi/\lambda$, the direction-coupling coefficient (C_θ) can be expressed as formula (21) after integral.

$$C_\theta = \frac{2\omega_{10}\omega_{20}}{(\omega_{10}^2+\omega_{20}^2)^{1/2}(\omega_{20}^2+\omega_{10}^2\cos^2\theta)^{1/2}} \times \exp\left[-\frac{\pi^2\omega_{10}^2\omega_{20}^2\sin\theta}{\lambda^2(\omega_{20}^2+\omega_{10}^2\cos^2\theta)}\right] \quad (21)$$

Suppose $\omega_{20} = \omega_{10}$, then C_θ can be simplified to formula (22).

$$C_\theta = \left(\frac{2}{1+\cos^2\theta}\right)\exp\left[-\frac{\pi^2\omega_{10}^2\sin^2\theta}{\lambda^2(1+\cos^2\theta}\right] \quad (22)$$

For small values of θ, C_θ can be written as formula (23).

$$C_\theta = \exp\left(-\frac{\theta^2}{2\theta_0^2}\right) \quad (23)$$

θ_0 is the divergence angle and can be expressed as $\theta_0 = \lambda/\pi\omega_{10}$. As shown in Figure 6, the greater the beam waist radius of the injected laser, the more sensitive the direction-coupling coefficient is.

As mentioned above, the coupling coefficient depends on not only the design of the master and slave laser, including the Gaussian beam radius, divergence

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angle, and beam waist location, but also the adjustment of the injected process, including radial deviation, direction deviation, and so on. The requirements of the radial calibration are higher when the value of ω_{20} is small.

2.1.6. *Cross-coupling between fundamental mode of master laser and multimode of slave laser*

In the actual situation, fundamental mode of master laser may be cross-coupled with multimode of slave laser. It might cause the amplitude loss of useful locked-signal or even produce false signals. The expression of normalized coupling coefficient between fundamental mode of master laser and multimode of slave laser had been presented by Kogelnik, as shown in formula (24) [11].

$$C_{00MN} = \frac{M!N!}{2^{M+N}\left(\left(\frac{M}{2}\right)!\left(\frac{N}{2}\right)!\right)} C_0 (1 - C_0)^{\frac{M+N}{2}} \qquad (24)$$

where $C_0 = \frac{4}{\left(\frac{\omega_{10}}{\omega_{20}} + \frac{\omega_{20}}{\omega_{10}}\right)^2 + \left(\frac{\lambda Z_0}{\pi \omega_{10} \omega_{20}}\right)^2}$, M, and N are the orders of the transverse mode, ω_{10} is the beam waist radius of seed laser after transforming by the coupling system. Z_0 is the longitudinal distance from position of waist radius ω_{10} to position of waist radius ω_{20}. And the resonant frequency of TEMmnq mode might be expressed as formula (25) [12–14].

$$v_{mnq} = \frac{c}{2n_s L}\left[q + \frac{1}{\pi}(m + 2n + 1) \arccos \sqrt{g_1 g_2}\right] \qquad (25)$$

According to the interferometer principle, resonant-coupling output happens only when the injected laser field is consistent with the eigenmodes of interferometer. Therefore, the transverse mode can be observed by changing the cavity length of interferometer. Different patterns appear when the seed laser injected into different higher order modes of slave laser, for example, as shown in Figure 7. The power loss of seed laser coupled to the fundamental mode of slave laser will be inevitably. And correct-landscape mode selection is also needed. Therefore, adjusting the coupling system is necessary. The power of seed laser injecting into the fundamental mode of slave laser can be guaranteed.

2.2. *Longitudinal mode matching between master laser and slave laser*

Two approaches can be used to realize longitudinal mode matching between master laser and slave laser. One is adjusting the output frequency of the seed laser and the other is adjusting the resonant frequency of slave laser. The purpose of longitudinal mode matching is reducing the detuning of master laser and slave laser and achieving stable injection-locked laser output.

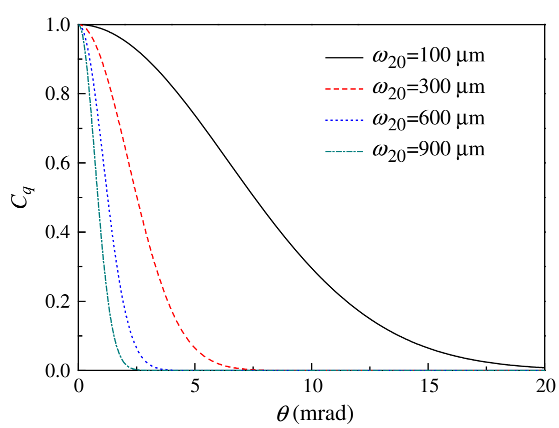
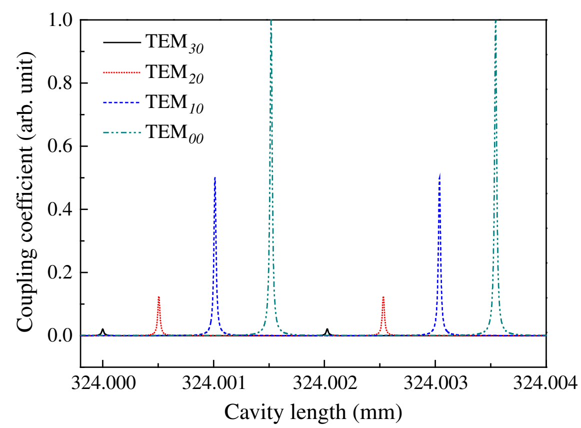
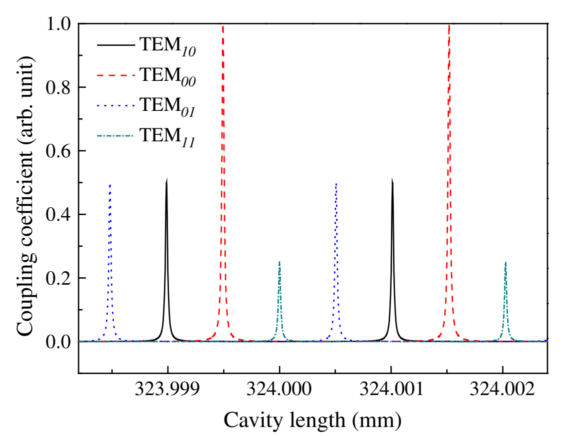


Figure 6. Direction of propagation coupling coefficient vs. the angle between two beams (a) TEM_{00} coupling with TEM_{00}, TEM_{10}, TEM_{20}, and TEM_{30} and (b) TEM_{00} coupling with TEM_{10}, TEM_{00}, TEM_{01}, and TEM_{11}. (The color version of this figure is included in the online version of the journal.)



(*a*) TEM_{00}coupling with TEM_{00}, TEM_{10}, TEM_{20}, TEM_{30}



(*b*) TEM_{00}coupling with TEM_{10}, TEM_{00}, TEM_{01}, TEM_{11}

Figure 7. Coupling coefficient between TEM_{00} of master laser and TEM_{mn} of slave laser. (The color version of this figure is included in the online version of the journal.)

The relationship of the output frequency of seed laser v_1 and the number of longitudinal mode q_1 could be expressed as formula (26).

$$v_1 = q_1 \frac{c}{2(\sum_i (n_i - 1)l_i + L_{1\text{cav}})} \tag{26}$$

where n_i is the refractive index and l_i is the length of the i-th based optical components in the cavity of seed laser. $L_{1\text{cav}}$ is the physical cavity length of seed laser.

The frequency interval of the ring resonator is shown in formula (27).

$$\Delta v_2 = \frac{c}{\sum_j (n_j - 1)l_j + L_{2\text{cav}}} \tag{27}$$

where n_j and l_j are the refractive index and length of the j-th based optical components in the cavity of slave laser, respectively. $L_{2\text{cav}}$ is the physical cavity length of slave laser.

Inconsistency existed between injected seed laser and the resonant frequency of the slave laser, as shown in Figure 8.

In order to realize longitudinal mode matching between master laser and slave laser, the cavity length of the slave laser resonator should be controlled. In experiment, one resonator mirror is fixed to a piezoelectric ceramic whose stretching is controlled by changing the voltage on it. Then, the resonant frequency of the slave laser is changed. When the resonance frequency of slave laser is coherent with the seed laser, injection-locked signal can be extracted effectively. Utilizing this injection-locked signal, Q-switch is triggered and Q-switched laser can be achieved. The process of injection locking is shown in Figure 9.

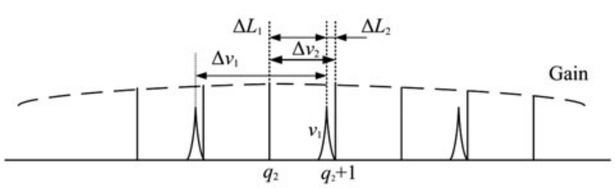


Figure 8. Schematic of the frequency difference between master laser and slave laser.

3. Experimental design of the injection-locked signal extraction

To realize injection locking, the injection-locked signal must be extracted efficiently. It means that both horizontal mode matching and longitudinal mode matching are required in the experiment. Experimental setup of injection-locked signal extraction is shown in Figure 10. Horizontal mode matching is completed by lens F1, F2 and flat mirrors P1, P2. Longitudinal mode matching is completed by the servo system. In order to avoid the optical damage to the seed laser caused by bidirectional output of the slave laser, an isolator (OFR) is inserted between the master laser and slave laser. Further, in order to achieve the polarization matching, $\lambda/2$ wave plate is inserted in the injection optical path.

3.1. Experimental design of horizontal mode matching

By thin lens transform of Gaussian beam, if the beam radius, and also the distance of the position between

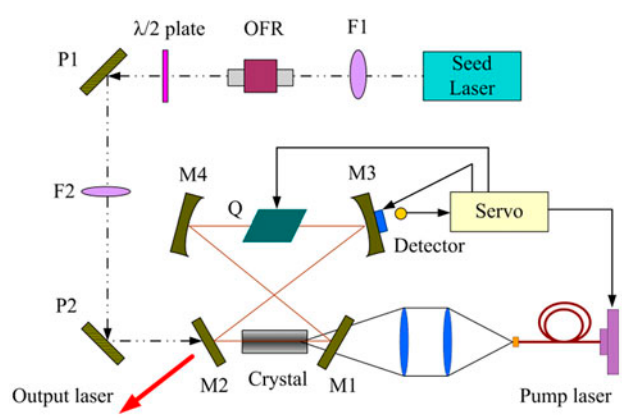


Figure 10. Schematic diagram of injection-locking laser. (The color version of this figure is included in the online version of the journal.)

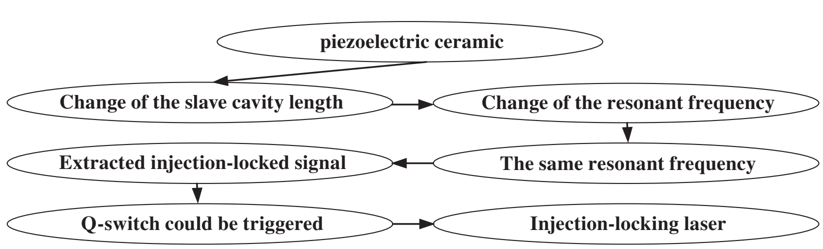


Figure 9. Process of injection locking.

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master laser and slave laser are known, horizontal mode matching can be realized by determining the position and focal length of the lens.

To reduce the size of the entire system, two lenses and two flat mirrors are used for horizontal mode matching. The beam radius of oscillating beam in the cavity can be achieved using LASCAD software, as shown in Figure 11(*a*).

For slave laser, the beam radius of oscillating laser at laser crystal is 0.42 mm and the divergence angle is 1.9 mrad. The radius of 0.2 mm and the divergence angle of 3.8 mrad of master laser are measured by the knife-edge method. The distance between the waist of master laser and slave laser is 500 mm. The focal lengths of two lenses for horizontal mode matching are 75 mm (F1) and 150 mm (F2), respectively. The distance between the waist of master laser and F1 is 77 mm. And the distance between the F2 and the waist of slave laser is 152 mm. The transmission of the injected seed laser in slave resonator can also be achieved using software, as shown in Figure 11(*b*). The radius and the divergence angle of the injected laser on the laser crystal of slave laser are 0.46 mm and 2.1 mad, respectively. The change process of injected laser is the same with the oscillating beam in slave laser. It is helpful to avoid exciting multimode and wasting energy of injected laser, which means that the energy of seed laser can be fully utilized.

3.2. Experimental design of longitudinal mode matching

One resonator mirror is fixed to a piezoelectric ceramic whose stretching is controlled by the servo system. Periodically, saw-tooth voltage is loaded on the piezoelectric ceramic, which will control the change of slave cavity length periodically.

When the resonance frequency of slave laser is relative to the seed laser, optical signals will be received by the detector placed behind the curved mirror M3. The detected optical signals convert into electrical signals, which can be observed with an oscilloscope. When the resonance frequency of slave laser is the same with the seed laser, injection-locked signal can be extracted effectively. The principle of longitudinal mode matching is shown in Figure 12.

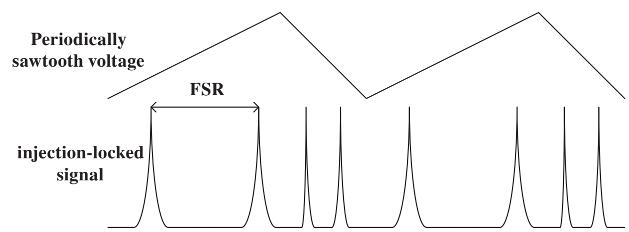

Figure 12. Longitudinal mode matching between master laser and slave laser.

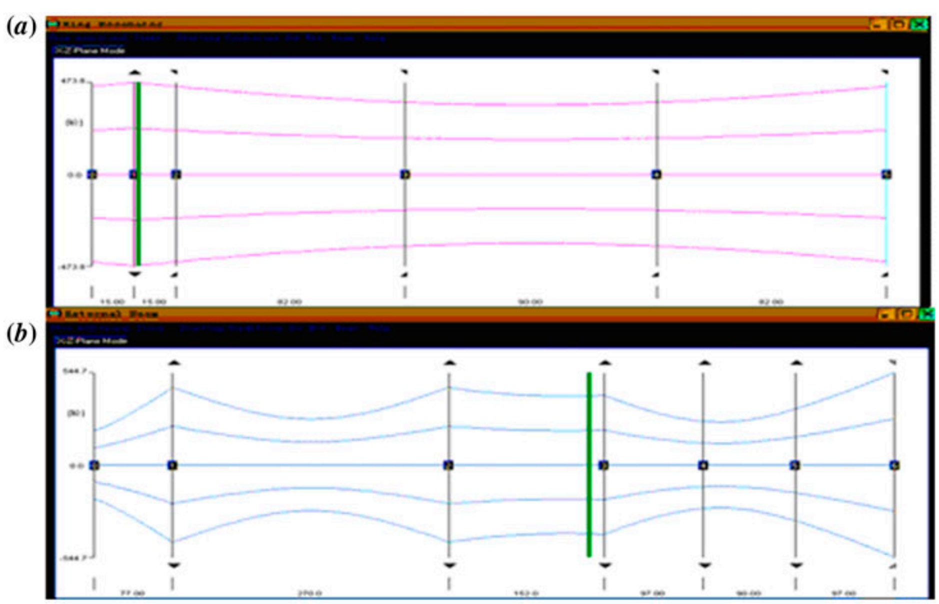

Figure 11. Propagation and transform of the laser beam (*a*) propagation of laser beam in slave laser (*b*) propagation of outside seed-laser beam. (The color version of this figure is included in the online version of the journal.)

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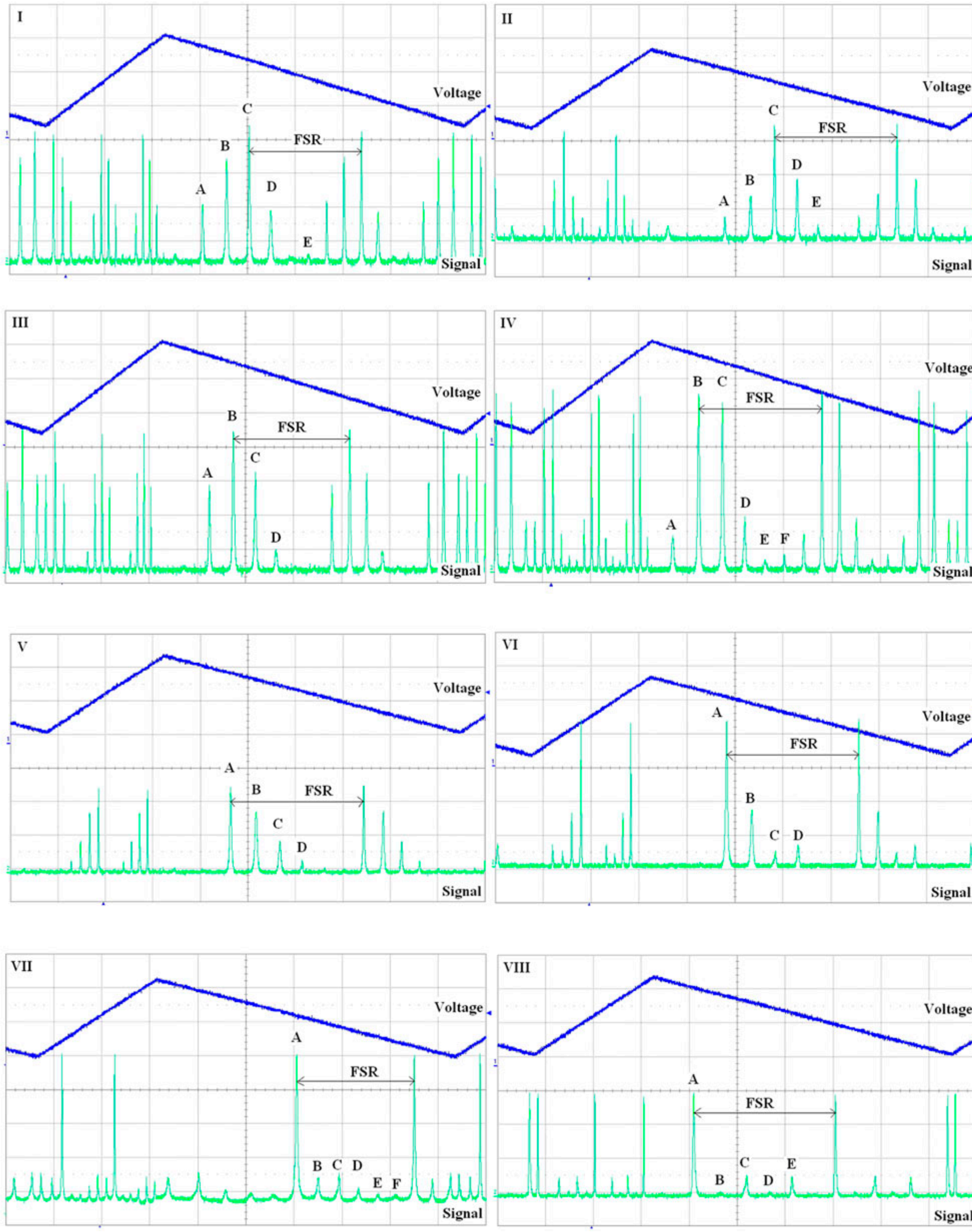

Figure 13. Signal extraction of frequency locking. (The color version of this figure is included in the online version of the journal.)

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4. Experimental results and analysis

4.1. Extraction process of injection-locked signal

The lenses of F1 and F2 are adjusted to change the longitudinal position and lateral position of the seed laser. The plan mirrors of M1 and M2 are convenient to control the direction of propagation of the seed laser. In experiment, by adjusting F1, F2 and P1, P2, the transformation patterns observed are shown in Figure 13. A, B, C, D, E, and F represent the modes.

As shown in Figure 13, despite the seed laser is single mode, a series of scanning signals is observed before suitably adjusted. The signals of I and V are similar with the examples in Figure 7. It means that the fundamental mode of injected seed laser is coupled to the higher order mode of slave laser. The final injection-locked signal is shown in Figure 13(VIII) because the mode matching of seed laser and slave laser cannot be adjusted exactly in practice.

4.2. Other factors affecting the locking signal extraction

As mentioned above, the seed laser injected into the passive resonator of slave laser is mainly considered. However, in fact, there are two factors, laser crystal and Q-switch, will impact the locked-signal extraction.

4.2.1. Temperature changes of laser medium in slave laser

The seed laser is coupled into the slave laser. Then, the temperature of the laser crystal in slave laser is changed by TE-cooler control. The relative intensity of the injection-locked signal changed, as shown in Figure 14.

As shown in Figure 14, when the temperature of laser medium in slave laser is lower than 8 °C, its absorption to the injected laser is very strong. As the temperature of laser crystal is between 10 and 20 °C, this absorption is weak. The absorption will enhance the competitiveness of the oscillating light, which owns the same frequency with the seed laser. However, if the absorption is too strong, the amplitude of the injection-locked signal is too weak to be the original source to control the servo system. The temperature of laser crystal in slave laser should be optimized. Also, the high accuracy of temperature is required to reduce the drift of the injection-locked signal.

4.2.2. Diffraction loss of Q-switch in slave laser

Diffraction loss of Q-switch will reduce the energy of the seed laser injected to the slave laser. As shown in Figure 15, resonant Signal 1 represented that no radio frequency (RF) loaded on Q-switch and resonant Signal 2 represented that the RF signal is acting at Q-switch. Especially, diffraction loss of the fundamental mode from Q-switch is the most seriously. Minimizing the RF power

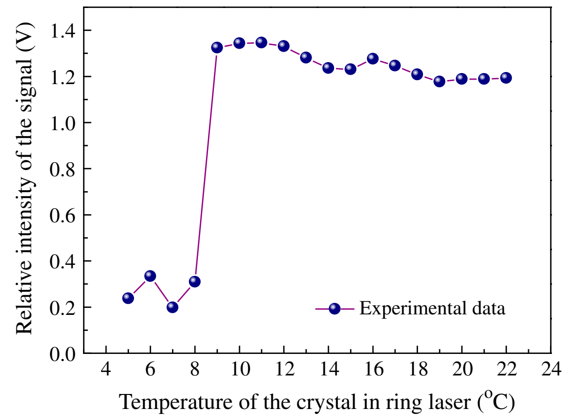

Figure 14. Relative intensity of the signal vs. temperature of the crystal in slave laser. (The color version of this figure is included in the online version of the journal.)

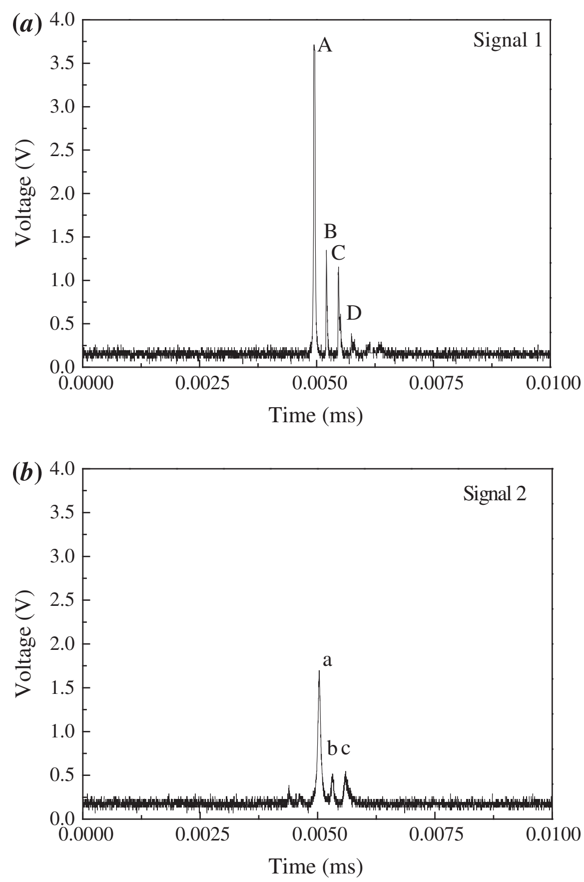

Figure 15. Locking signal under the Q-switch with and without RF (a) without RF and (b) with RF.

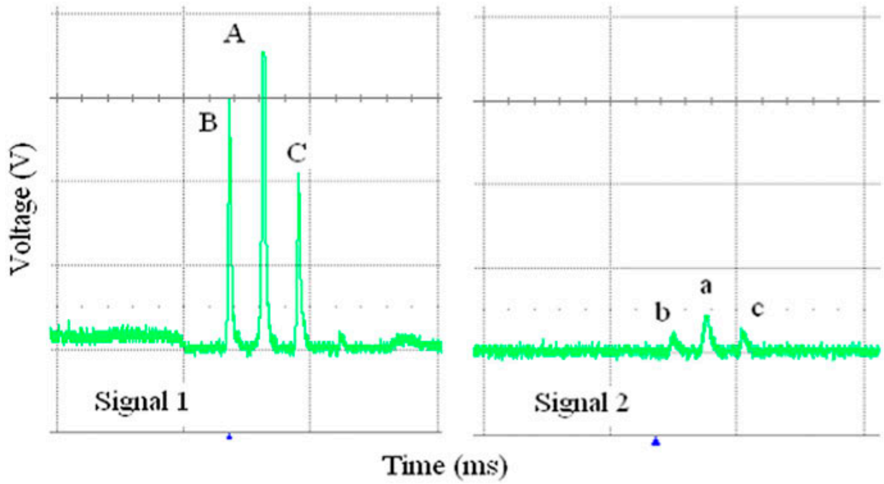

Figure 16. Locking signal under the Q-switch with and without RF. (The color version of this figure is included in the online version of the journal.)

on Q-switch, until it cannot play the role of Q-switching, is necessary.

If the fundamental transverse mode of seed laser is coupling into the multimode of the slave laser evenly, the amplitude of the injection-locked signal with no RF and RF loaded on Q-switch is shown in Figure 16. It is difficult to judge which signal is the fundamental transverse mode of slave laser. And the amplitude is too small to control the servo system.

5. Conclusion

In this paper, various factors influenced on the injection-locked signal extraction are analyzed. In order to achieve useful injection-locked signal, mode matching between master laser and slave laser is necessary. In theory, for horizontal mode matching, the same radius, the beam waist position, and the same direction of propagation of master laser and slave laser can improve the coupling coefficient. When the deviation cannot be avoided, the bigger oscillation spot is favorable. Therefore, oscillating spot should be designed to larger under the premise of large output pulse energy and pulse width. For longitudinal mode matching, the servo system is necessary to keep the consistent frequency of master laser and slave laser. According to the theoretical analysis, the focal lengths of two lenses for horizontal mode matching are designed. By adjusting the coupling mirrors and electrical servo system, the injection-locked signal is extracted successfully. Especially, by master the effect of crystal temperature and RF of Q-switch to the injection-locked signal, proper crystal temperature and RF of Q-switch are selected. All the works mentioned above are quite useful to improve the output characteristics of injection-seeded laser. At last, an injection-seeded Tm:YAG laser, pulsed single-frequency 2013 nm, with an output energy of 3.16 mJ, and a pulse width of 238.7 ns are achieved at a repetition rate of 100 Hz.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [grant number 61405017].

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