Littrow-type external-cavity diode laser with a triangular prism for suppression of the lateral shift of output beam

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We demonstrate a Littrow-type external-cavity diode laser with an additional triangular prism united to a diffraction grating. In this configuration, while the laser wavelength can be tuned by rotating the grating that constitutes an external cavity, the prism outside the cavity compensates for the lateral shift of the output beam. It is estimated that the lateral shift of the output beam is only 2 μm over the tuning range of 12.91 nm. In fact, the output beam was coupled into a single-mode fiber with constant efficiency over the wavelength range without any adjustment of the coupling optics. [DOI: 10.1063/1.2190287]

An external-cavity diode laser (ECDL) with a diffraction grating is a compact and cheap tunable light source with a narrow linewidth.[1–4] The Littrow-type ECDL schematically shown in Fig. 1(a) has the simplest design among the various types of ECDLs. In this scheme, the first-order diffraction light beam from the grating is fed back into a laser diode in order to create an external resonator, while the reflection light from the grating is taken out as an output beam. By rotation of the grating around a pivot, the wavelength can be tuned since the cavity length and the wavelength of the light fed back are changed. However, the Littrow-type ECDL has a disadvantage in that the direction of the output beam depends on the rotation of the grating, i.e., the wavelength, since the reflection angle of the light is equal to the incident angle. By simply using an additional plane mirror parallel to the grating as shown in Fig. 1(b) (Ref. 5) or by taking advantage of a transmission grating,[6] the direction can be independent of the wavelength, but the output beam is laterally shifted.

On the other hand, it is more difficult to make the types of ECDL in which the axis of the output beam is unchanged than it is to make the Littrow-type ECDL. In a scheme using an intracavity beamsplitter as an output coupler,[7] the beamsplitter must be of high quality to avoid losses and secondary cavity formation. In the Littman-Metcalf-type ECDL, where the first-order diffraction light from the grating is shone on an additional plane mirror and the light beam retroreflected by the mirror is diffracted again by the grating and fed back into a laser diode,[8,9] the wavelength can be tuned by rotation, not of the grating but of the mirror. Thus, the axis of the output beam, which is the reflection of the light from the laser diode by the grating, is independent of the wavelength. However, the design is more complex, and the output power becomes weaker than that in the Littrow-type ECDL since the light beam reflected by the grating after being turned back by the mirror escapes the cavity as a loss.

ECDLs have become the most frequently used laser diodes for atom physics such as laser cooling and trapping. In most experiments, Littrow-type ECDLs have been utilized regardless of the beam shift since it is necessary to continuously scan the frequency around the narrow resonance line by less than 10 GHz (0.01 nm in visible region in terms of wavelength). Recently, however, a tunable laser has been used for the creation of entangled photon pairs and second harmonic generation using a periodically poled lithium niobate (PPLN) waveguide in the study of quantum optics and nonlinear optics.[10–13] In the experiment, a laser beam is first coupled into a waveguide of several micrometers. Then, phase matching is obtained by tuning the wavelength to that decided by the period of domain inversion. Since the production process of PPLN disperses the period, the wavelength needs to be tuned over the wide range of ±1 nm. Thus, the shift of the laser beam by wavelength tuning affects the experiments.

In this article, to fix the axis of the output beam from a Littrow-type ECDL, we propose and demonstrate a simple scheme using an additional triangular prism. We also experimentally confirm the constancy of the axis over a wide range of tuning by the measurement of the coupling efficiency of the output beam into a micron-size core of a single-mode fiber. In this scheme, all we have to do for the beam fixing is to fasten the grating and the prism on the same board in order to arrange them in particular positions. In addition, since the prism is outside the external cavity, this scheme can be easily performed without regard to the quality of the prism. Moreover, the loss of laser power by the beam fixing is small since the loss is caused only by Fresnel reflection on the incident and output surfaces of the prism.

Figure 2(a) schematically shows a Littrow-type ECDL with the prism. The prism forms a pillar whose bottom surface is a right-angle isosceles triangle. For the following explanation, as shown in Fig. 2(a), the three sides of the prism

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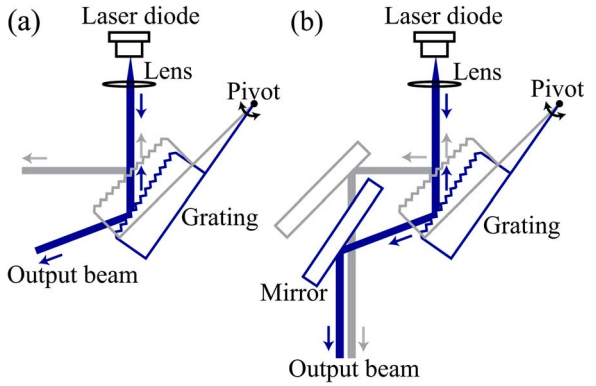

FIG. 1. A sketch of a normal Littrow-type ECDL (a) and one with an additional plane mirror parallel to the grating surface (b). Here, the change of the output beam axis by the rotation of the grating is expressed with gray lines. The ECDL consists of a laser diode, a collimation lens, and a grating. The first-order diffraction light from the grating is turned back into a laser diode in order to generate an external cavity. On the other hand, the reflection light is taken as an output beam. Since the wavelength depends on the rotation angle of the grating around the pivot, in the case of (a) the direction of the output beam changes with the wavelength tuning. On the other hand, in the case of (b), where the mirror rotates with the grating, the output beam is always parallel to the incident light to the grating. However, the output beam is laterally shifted by the rotation for the tuning.

are labeled A, B, and C. Both the grating and the prism are fastened to a board so that side B is parallel to the grating surface independent of the rotation around the pivot. A light beam from a laser diode is collimated with a lens and is incident to the grating. Here, the wavelength of the first-order diffraction light fed back to the laser diode is given as

$$\lambda = 2d \sin \theta, \tag{1}$$

where d and θ are the period of grating lines and the incident angle to the grating, respectively. The period d is selected for the wavelength so that Eq. (1) can be satisfied at the incident angle $\theta \approx 45°$. We now assume that the incident angle becomes $\theta = 45° + \alpha$ by rotation of the board as shown in Fig. 2(a). The light reflected by the grating is bent by 2α and illuminates side A at the incident angle of α. After refraction at the angle of $\beta = \arcsin[(\sin \alpha / n)]$ (n: the relative refractive index of the prism) according to Snell's law, the light beam shines incident to side B at the angle of $45° + \beta$ and is totally reflected when $n > 1/\sin(45° + \beta)$. Then, the light beam reaches side C at the angle of β and refracted at an angle of α and output. As the prism rotates by α, the output beam is parallel to the incident beam into the grating independent of the rotation, that is, to say, the wavelength.

The displacement of the output beam, which we now express using the distance between the output beam and the incident beam to the grating x is obtained as a function of rotation α by straightforwardly tracing the beam in the ECDL system according to geometric optics,

$$x(\alpha) = [(\sqrt{2}R_B - R_A + R_C)\tan \beta + \sqrt{2}(R_B - R_G)]\cos \alpha + (R_A - R_C - \sqrt{2}R_G)\sin \alpha, \tag{2}$$

where R_A, R_B, R_C, and R_G are the distances from the pivot to the planes including the prism sides A, B, C, and the grating surface, respectively. Remarkably, the displacement $x(\alpha)$ is independent of the distance from the pivot to the laser beam

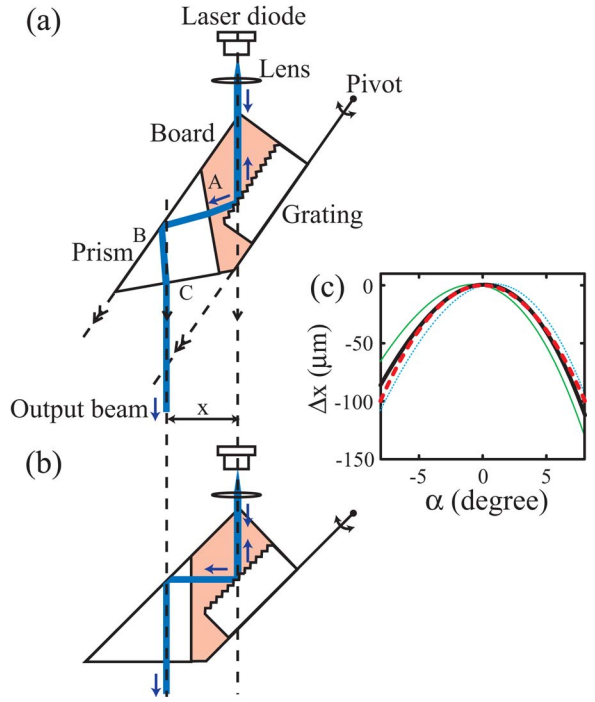

FIG. 2. Littrow-type ECDL with a triangular prism to fix the output beam. The configuration shown in (a) is the same as that indicated in (b) except for the rotation angles $\alpha > 0$ (a) and $\alpha = 0$ (b). The grating and the prism are mounted on a board so that side B of the prism is always parallel to the grating surface. We can see from geometric optics that the output beam is always parallel to the incident beam to the grating. Moreover, the lateral shift of the output beam by rotation of the grating is strongly suppressed by refraction and the total internal reflection on the surfaces of the prism. (c) The residual lateral shift Δx as a function of rotation α. Here, the thick solid line and the broken line show $\Delta x(\alpha)$ which are explicitly calculated with Eq. (2) and approximately given by Eq. (5), respectively. The thin solid and dotted curves present $\Delta x(\alpha)$ for the case where R_G deviates by 0.1 and −0.1 mm, respectively.

incident on the grating, R_{LD}. Here, we can expand $x(\alpha)$ into a polynomial function of α,

$$\begin{aligned} x(\alpha) &= A_0 + A_1\alpha + A_2\alpha^2 + O(\alpha^3) \\ &= \sqrt{2}(R_B - R_G) + \left[\left(1 - \frac{1}{n}\right)(R_A - R_C) - \sqrt{2}\left(R_G - \frac{R_B}{n}\right)\right]\alpha - \frac{R_B - R_G}{\sqrt{2}}\alpha^2 + O(\alpha^3). \end{aligned} \tag{3}$$

Each coefficient of Eq. (3) is decided by the configuration of the ECDL system. Here, when $\alpha \ll 1$ rad, $dx(\alpha)/d\alpha \simeq A_1$. Therefore, if we choose a configuration such that $A_1 = 0$, the change of the displacement by rotation is largely suppressed. The condition for the configuration can be obtained from Eq. (3) as

$$(n-1)(R_C - R_A) + \sqrt{2}(nR_G - R_B) = 0. \tag{4}$$

Figure 2(b) schematically shows the trace of the light at the rotation angle $\alpha = 0$ in order to compare the displacement with that at the rotation angle $\alpha > 0$ shown in Fig. 2(a). We can find from Figs. 2(a) and 2(b) that the output beam is fixed independently on the rotation angle due to refraction and the total internal reflection on the surfaces of the prism.

A residual lateral shift $\Delta x(\alpha)$ is approximately given by the second-order term of Eq. (3),

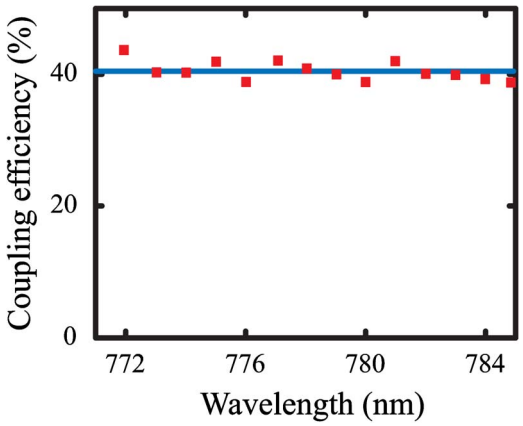

FIG. 3. The wavelength dependence of the coupling efficiency into a single-mode fiber with an MFD of 5.5 μm. Here, the dots and the line indicate the experimental values and the average overall experimental values, respectively. The coupling efficiency is constant over a wide tuning range of 12.91 nm.

$$\Delta x(\alpha) \simeq -\frac{R_B - R_G}{\sqrt{2}}\alpha^2. \tag{5}$$

The thick solid and broken lines in Fig. 2(c) present the residual lateral shifts $\Delta x(\alpha)$ which are explicitly calculated with Eq. (2) and approximately given by Eq. (5), respectively. Here, we take $1/d=1800$ lines/mm, $R_A=39.0$ mm, $R_B=29.2$ mm, $R_C=27.8$ mm, $R_G=22.0$ mm, and $n=1.51$ as a typical case in which Eq. (4) is satisfied. One can see that the approximation by Eq. (5) is valid within an error of 10% when $|\alpha|<5°$, which corresponds to a wavelength range of 137 nm.

In order to experimentally confirm the fixing of the output beam axis, the output beam from a Littrow-type ECDL with a prism was coupled into a single-mode fiber with a mode field diameter (MFD) of 5.5 μm. We examined the wavelength dependence of the coupling efficiency in the case where the optical axis was not adjusted for the coupling over the tuning. In the application where a tunable laser beam is coupled into an optical fiber or a waveguide, it is very informative to measure the coupling efficiency in its tuning range. In the experiment, the output from a laser diode with a center wavelength of 778 nm was collimated with an antireflection-coated aspheric lens with a focal length of 4.51 mm and then diffracted by a grating with a first-order efficiency of 40%. Here, $R_{\mathrm{LD}}=33.5$ mm. The cavity length, i.e., the distance from the laser diode to the grating, was 15 mm. The triangular prism was made of BK7 glass with two 30 mm sides. The board on which the grating and prism were mounted was gripped by a mirror mount for horizontal rotation for tuning and vertical tilt adjust. These components were set on the $80\times80\times10$ mm^3 aluminum substrate and put into an aluminum box. The temperature was measured by a 10 kΩ thermistor embedded into the substrate and stabilized on 24 °C by a Peltier device sandwiched between the substrate and the bottom of the box. The output beam was coupled into the fiber 55 cm away from side C of the prism using a fiber optics beam coupler with a focal length of about 10 mm after passing through a 40 dB optical isolator.

Figure 3 shows the coupling efficiency as a function of the wavelength. The coupling efficiency had a constant value of 40% over the wide tuning range of 12.91 nm (771.93 nm$\leqslant\lambda\leqslant$784.84 nm). Since the MFD of the waveguide of a typical PPLN is almost equal to that of the fiber, it can be found that the lateral shift of the output beam was sufficiently suppressed for experiments using PPLNs.

In the configuration, it can be derived from Eq. (1) that the wavelength tuning from $\lambda=771.93$ nm to $\lambda=784.84$ nm corresponds to the rotation from $\alpha=-0.99°$ to $\alpha=-0.06°$, and the residual shift by the tuning, i.e., $\Delta x(-0.99°)-\Delta x(-0.06°)$ is calculated from Eq. (5) to be only 2 μm. On the other hand, if we put a plane mirror at the position of side B instead of the prism, the lateral shift by the tuning is estimated to be approximately $\sqrt{2}(R_B-R_G)\Delta\alpha=165$ μm by substituting $n=1$ into Eq. (3), where $\Delta\alpha$ is 0.93° in our case. Although the focal point of the incident beam into the fiber is unchanged in principle even if the output beam from a laser source is laterally shifted, the incident angle into the fiber is changed. If the focal length is assumed to be 10 mm as a typical value, the 165 μm lateral shift increases the incident angle by 0.0165 rad (0.95°). The tilt should affect the mode excitation in the core of the fiber. In addition, while the numerical aperture (NA) of the incident beam must be 0.089 in order to obtain a beam waist identical to the MFD of the fiber, 5.5 μm, the tilt increases the NA to 0.106. This value approaches to the permissible maximum NA of the fiber in a typical case, 0.12. Therefore, the tilt can induce a loss due to the incompletion of the total internal reflection inside the fiber. On the other hand, by the scheme using a triangular prism, the tilt angle becomes only 2×10^{-4} rad (0.01°) in the 12.91 nm tuning in the case of a 10 mm focal length. Therefore, the lateral shift can be sufficiently suppressed for efficiently coupling the light into a micron-sized waveguide.

Finally, we discuss some possible errors that might degrade the characteristics of our device from the ideal condition. One might be caused by the geometrical misalignment of the optical components. From Eq. (2), the lateral shift of the output beam in our tuning range is given as $x(-0.99°)-x(-0.06°)=(-5.5R_A-15R_B+5.5R_C+23R_G)\times10^{-3}$. Therefore, the lateral shift in our experiment is the most dependent on the misalignment of the grating position. For instance, if R_G deviates by 0.1 mm from the ideal value, the additional shift of the output beam would be 2.3 μm in our tuning range. This value is still much smaller than that expected (165 μm) in the case of using a mirror instead of a prism discussed above. The thin solid and dotted curves in Fig. 2(c) present $\Delta x(\alpha)$ estimated with Eq. (2) for the case where R_G deviates by 0.1 and −0.1 mm, respectively. One can see that the quadratic part still dominates the beam shift for $|\alpha|\gtrsim1°$. The other error might originate from the dispersion of refractive index of the prism. However, since the change in the index of BK7 glass in our tuning range is in the order of 10^{-4}, the effect on the beam shift is quite small (in the order of 0.1 μm), and the effect of the dispersion is thus negligible.

In conclusion, we proposed and demonstrated a Littrow-type ECDL using a triangular prism to fix the output beam. The output beam was coupled into a single-mode fiber with constant efficiency over a wide tuning range of 12.91 nm without alignment for the coupling after the tuning. With this scheme, we can simply and cheaply make a tunable laser source for coupling into a micron-sized waveguide to replace

much more expensive laser systems such as a $Ti:Al_2O_3$ laser. It will be applied to the creation of entangled photon pairs as well as second harmonic generation using PPLNs.

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