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Diode laser coupled to a high-Q microcavity via a GRIN lens

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ABSTRACT A miniature high-coherent diode laser was developed. Optical feedback from a high-Q microsphere resonator was used to narrow the spectrum of the laser, and a nearly half-pitch gradient-index lens served as a coupling element. As estimated from the variation in frequency-tuning range (chirp-reduction factor) the fast line width of the laser was reduced by more than three orders. It is remarkable that the system reveals stable single-mode operation at a relatively high feedback level. A tentative explanation is presented in terms of previously given models.

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1 Introduction

The diode laser (DL) spectrum has to be narrowed to make it suitable for many applications requesting a line width below 1 MHz (high-resolution spectroscopy, metrology, and data communication). At the present time the technique of optical feedback is a common means to improve the DL temporal coherence. The last becomes possible due to the increase of a laser-cavity Q-factor. Unfortunately, a significant Q-factor is usually achieved at the expense of laser compactness, which is one of the DL advantages over other types of lasers. A high-Q 'whispering-gallery' microsphere resonator (WGMR) described in [3] combines such previously incompatible properties as high quality factor and sub-millimeter sizes. Moreover, the Rayleigh backscattering in fused silica provides a natural mechanism of optical feedback (OFB). For the first time DL line-width narrowing by means of optical feedback from a WGMR was demonstrated in [4]. However, a bulky coupling prism and objectives did not allow taking advantage of an exceptionally small quartz sphere. The decrease of the distance between a DL and a high-Q cavity is particularly attractive since (i) there were several implications [1, 5] that it may suppress some types of dynamical instabilities which limit the line-width narrowing; (ii) it decreases the amplitude noise which accompanies phase-noise suppression; (iii) it gives the possibility to exclude active stabilization of the distance by a 'phase mirror', resulting in frequency and amplitude modulation; and (iv) smaller sizes provide greater tolerance to temperature and mechanical perturbations. In this letter we report on a compact high-coherent light source comprising a diode laser coupled to a microsphere resonator via a gradient index (GRIN) lens (Fig. 1). This technique of coupling was proposed in [5], where the frequency stability and tunability of the microsphere-stabilized laser were also discussed.

2 Experiment

A narrow-stripe DL of a Fabry–Pérot type was mounted on a temperature-stabilized heat sink. The operating wavelength was 780 nm, and two outputs provided 5 mW from the front facet and about 1 mW from the rear facet. The front-facet radiation was sent into a fused-silica microsphere of about 800 μm in diameter, while the beam from the rear facet was collimated by an objective (O) and was used in diagnostics. Two quarter-pitch gradient-index rods made of Selfoc® (SLS type) collected laser light from the front facet and focused it into the lens–microsphere contact zone. The coupling zone was formed by polishing the butt end of a Selfoc® rod at the angle $\alpha = \arcsin(n_{\text{quartz}}/n_{\text{Selfoc}}) = 69°$ with n_{quartz} and n_{Selfoc} being the refractive indices of the microsphere and the rod lens (at the axis), respectively. This provided the excitation of low-order 'whispering-gallery' (WG) modes via an evanescent field, which appears in the frustrated total internal reflection. In our experiment the clearance between the rod lenses was used for final adjustment, but it might also serve as the output for commercial single-output diode lasers if a thin beam splitter is inserted. The optimum position of the microsphere in the plane of the polished facet was found with a translation stage having a resolution of about 0.1 μm. This position was then fixed with a glue droplet (GD) placed between the microsphere stem and the laser base. Since the quality factor of a WGMR and, consequently, the intensity of the backscattered wave critically depend on loading [2], the gap between the sphere and the GRIN lens was controlled by a piezo actuator (PZT).

The large-scale spectrum of the optically locked laser was analyzed by means of a monochromator with a resolution of 0.1 nm. Being coupled to a WG mode the laser module operated at a single frequency. By changing current it was possible to obtain switching from one mode to another, separated by

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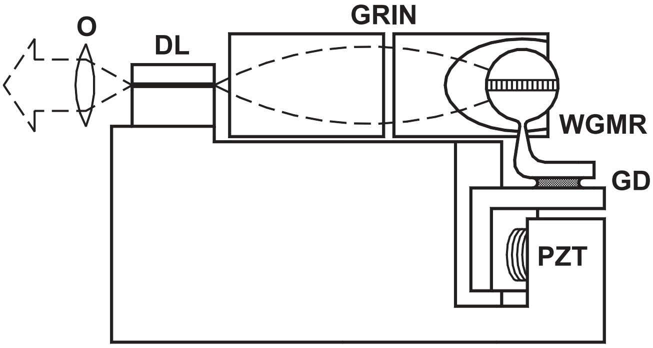

FIGURE 1 Experimental set-up. O, objective; DL, diode laser; GRIN, a pair of quarter-pitch gradient-index lenses; WGMR, 'whispering-gallery' microsphere resonator; PZT, piezo actuator; GD, glue droplet

about 1 nm. The switching is governed by the temperature tuning of DL eigenmodes and their coincidence with different WG modes. It is facilitated by the initial multimode spectrum of a solitary DL.

Laser spectra were also monitored with a scanning confocal Fabry–Pérot cavity (CFP) having the resolution of 16 MHz. Figure 2 displays the spectra over several modes of the CFP for the free-running regime of a DL and for a DL locked to a WG mode. The free-running spectrum owing to multimode oscillation is so entangled that the free spectral range of the Fabry–Pérot cavity is hardly distinguishable (Fig. 2a). It becomes a pure single mode under OFB conditions, and the width of the recorded spectrum is resolution-limited (Fig. 2b). Interestingly, the previous experiments on the line-width narrowing by means of an optical feedback from an external high-Q cavity of the Fabry–Pérot type required single-mode operation of a solitary diode laser.

To estimate the laser line-width narrowing we measured the rate of frequency tuning with pumping current $d\nu/dI$ for the free-running laser and the laser locked to a WG mode. The chirp-reduction factor was found to be $S = (d\nu_0/dI)/(d\nu_{WGMR}/dI) \approx 35$. Under the assumption of a uniform frequency distribution of the phase noise, the line-width narrowing can be evaluated as $S^2 \approx 1200$ [1, 2].

Figure 3 demonstrates the dependences of the DL output power on pumping current that is swept back and forth. The difference in the output power between the free-running laser (Fig. 3a) and the laser under optical feedback (Fig. 3b) amounts to a few tens of per cent of the initial value. Note that, in contrast to [5–7], we readily see an influence of the locking to the modes of the high-Q cavity in the direct output of the laser, not only in the transmission of the cavity used for the optical locking. Large, hysteresis-accompanied variations of power induced by optical feedback imply a relatively high feedback level. We estimate it (from relative change of power with feedback, threshold current, and differential efficiency) to be about 10^{-2}. This feedback level is at least one order greater than those given in [5–7], where feedback efficiency was limited by perturbations of the single-mode regime by parasitic modes and/or enhanced relaxation oscillations.

3 Discussion

Here we compare the locking of a DL to the mode of a standard confocal cavity (via transmission resonance) and to the WG mode of the microsphere (via Rayleigh backscattering) and present a tentative explanation of the regime stability at a high feedback level. The chirp-reduction factor for zero detuning and optimum phase of the feedback is [1]:

$$S = 1 + \varepsilon^{1/2}(1+\alpha^2)^{1/2}(\gamma_{DL}/\gamma_0) , \qquad (1)$$

where ε is the intensity feedback level, α is the line-width enhancement factor, and γ_{DL} and γ_0 are the line widths (FWHM) of the DL cavity and the microcavity, respectively. The line-width narrowing for a given S depends on the type of noise: for white noise it is S^2, while for technical noise it is S [1, 8]. The $1/f$ noise can produce deviation from Lorentzian shape [7]. In any case the maximum line-width reduction increases with ε (for given values of α, γ_{DL}, γ_0). However, this feedback level is limited. According to [1] the stable regime

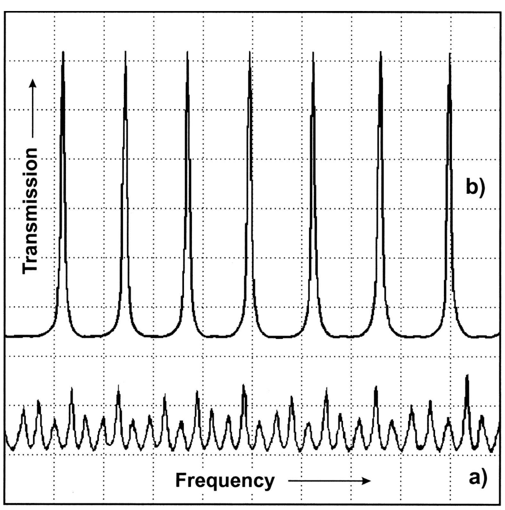

FIGURE 2 Transmission of a reference confocal Fabry–Pérot cavity for the free-running diode laser (a) and the laser under optical feedback (b). The cavity free spectral range is 240 MHz

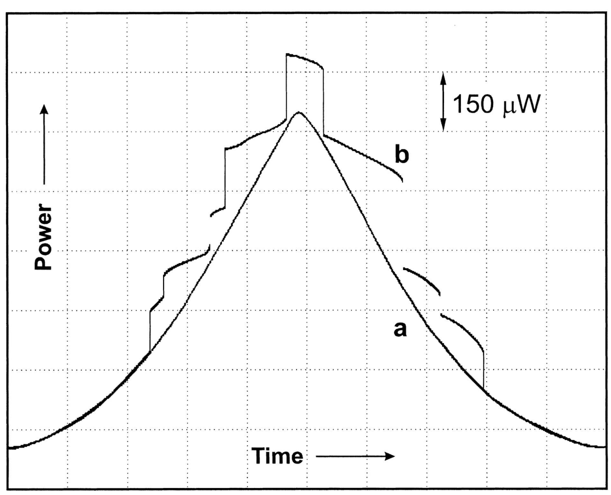

FIGURE 3 The oscillograms display power vs current dependences for the free-running laser (a) and the laser under optical feedback (b). The DL current is modulated with a symmetrical ramp. A hysteresis in the power level gives the asymmetry of the curve (b)

is possible only if the intensity feedback level (ε) is small enough:

$$\varepsilon < 4(f_R/\gamma_{DL})^2(1+\alpha^2)^{-1} , \qquad (2)$$

where f_R is the relaxation oscillation frequency. As a result the maximum chirp-reduction factor is limited by $S < 2 f_R/\gamma_0$. The simple form of the given inequalities holds if $S \gg 1$, which is true in our case. By taking $f_R = (0.5–1)$ GHz (the DL operates at moderate excess above threshold), $\gamma_{DL} =$ (20–40) GHz, and $\alpha = 3-5$, we get $(3\times10^{-5}–10^{-3})$ for the right-hand side of inequality (2). Our feedback level estimated earlier (10^{-2}) is greater by at least one order of magnitude. Before we turn to this point we briefly compare the S factor for a bulky (typically confocal) interferometer and a WGMR.

The chirp-reduction factor or a stabilization parameter in the case of coupling of a DL to a WG mode of a microsphere equals [2]:

$$S_{WG} = 1 + F(\varphi)\beta(\tau_0/\tau_c)(\gamma_{DL}/\gamma_0)(K/(1+K^2)^2) . \qquad (3)$$

The geometrical coupling factor β together with the factor (τ_0/τ_c) gives the coupling efficiency. The total decay time of photons in a WGMR is $\tau_0 = (\tau_{00}^{-1} + \tau_c^{-1})^{-1}$ with τ_{00} and τ_c being the lifetimes of photons determined by intrinsic and coupling losses, respectively (it is convenient to keep both γ_0 and τ_0 in the formula, although they are related by $\gamma_0 = (2\pi\tau_0)^{-1}$). All listed factors give the same result as in [1, 7]. The new factor $K/(1+K^2)^2$ describes the specific way of feedback formation that is by Rayleigh scattering. Here $K = k\tau_0$, with k being a coupling coefficient of the two counterpropagating WG modes. If the loaded Q-factor and τ_0 become too small, the propagation length of the field of a WG mode falls, and Rayleigh backscattering inside the quartz microsphere decreases together with the feedback level. The numerator K is responsible for this dependence. As τ_0 increases K rises and can even become greater than 1 in experiments [5, 9]. The WG mode is split in two in the frequency domain and the stabilization factor at zero detuning decreases. This is described by the denominator $(1+K^2)^2$. Practically, it makes sense to work in the range $0.1 < K < 1$. The only factor left is $F(\varphi) = \alpha\sin(\varphi)+\cos(\varphi)$ (see (9) and (15) in [2]), which gives the dependence of S on the phase delay of the field during the round trip from the laser to the external cavity. This factor increases from 1 for $\varphi = 2\pi N$ (N an integer) to $(1+\alpha^2)^{1/2}$ at $\varphi = 2\pi N + \arctan(\alpha)$ and then falls to α at $\varphi = 2\pi(N+1/4)$. Actually, the same factor refers to the case of bulky cavities described by (1). However, in the last case the phase is typically stabilized in the vicinity of $\varphi = 2\pi N + \arctan(\alpha)$ and this condition is most often considered. Thus, leaving aside specific formation of the counterpropagating wave and the dependence on K, the S factors given by (1) and (3) are basically the same and the instability condition (2) should work in our case too. However, it does not.

To explain it we use the qualitative model of instability origin proposed in [1]. A frequency fluctuation of the laser changes the phase difference between the laser and feedback fields after a transit time of the external cavity. For the feedback field being in quadrature with respect to the laser field, a small fluctuation in its phase changes mainly the amplitude of the total field. It is followed by the relevant gain fluctuation, which results in a frequency change due to the amplitude–phase coupling. This frequency response suppresses the initial frequency fluctuation. On increasing the feedback efficiency both the gain of the feedback loop and its bandwidth increase. When the bandwidth becomes greater than the relaxation frequency the feedback becomes unstable, since the response of the gain-to-frequency conversion acquires an additional phase shift at the high-frequency edge of the bandwidth.

For a bulky cavity the distance between a DL and the cavity is large. To stabilize it the feedback phase is deliberately modulated so as to produce a small frequency modulation and to get an error signal in the cavity transmission. It works for the mean value of the phase delay being close to quadrature ($\alpha \geq 3$). In our case the DL–microsphere distance is small and passive stabilization of the laser current and its temperature is enough for durable observation of the optical locking. So, it was possible to work in in-phase condition where the α factor is not involved in the first approximation in the feedback mechanism. Laser frequency fluctuations are suppressed by phase variations and do not involve an amplitude change in the first approach. The stabilization parameter S becomes smaller due to $F(\varphi)$ by a factor of about α. However, the feedback level is not limited and its increase may be greater than α. The detailed analysis will be published elsewhere.

4 Summary

In conclusion, we have developed a miniature high-coherent diode laser. The laser spectrum was narrowed using the optical feedback from a high-Q microsphere resonator, and a slanting-butt rod lens served as a coupling element. The fast line width of the laser was reduced by more than three orders, and stable operation at a high level of the OFB was demonstrated and qualitatively explained.

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