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High-coherence diode laser with optical feedback via a microcavity with 'whispering gallery' modes

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Abstract. Narrowing of the linewidth of a diode laser was achieved by an external high-Q microcavity, which was a fused silica sphere 370 μm in diameter. Coupling of the radiation in and out, and matching to a 'whispering gallery' mode of this sphere, were ensured by the method of frustrated total internal reflection. Optical feedback was provided by the Rayleigh scattering. The width of the beat-note spectra of the investigated and reference lasers did not exceed 100 kHz.

The applications of diode lasers have recently become much wider because methods for narrowing the linewidth have been developed. One of the most effective methods relies on optical feedback. Two modifications of this method are known and they are capable of approximately the same narrowing of the emission spectrum: an increase in the cavity Q factor by increasing the cavity length practically without any change in the number of passes, which provides a strong (~ 0.1) coupling to an external reflector or diffraction grating [1], and the use of a weak (of the order of 10^{-4}) coupling to an external high-Q (multipass) cavity. In the latter case, a confocal [2] or a fibre ring [3] interferometer is used. Unfortunately, the output coherence is increased at the expense of an increase in the size of the laser and of its sensitivity to mechanical perturbations.

We investigated a new variant of an external high-Q cavity in the form of a fused silica microsphere in which 'whispering gallery' (WG) modes are excited. The properties of such microcavities, which have a high Q factor and are compact, are described in Ref. [4]. Light is coupled in and out of a microcavity by the method of frustrated total internal reflection with the aid of a coupling prism. The diameter of the silica microsphere was $D = 370$ μm and the free spectral range was $\Delta\nu = c/\pi D n = 170$ GHz, where $n = 1.4$ is the refractive index of silica. An alignment device made it possible to vary the gap between the coupling prism and the microsphere, and thus vary the degree of coupling to the WG mode. The internal distributed losses of the WG mode were very low and its Q factor depended strongly on the degree of coupling. When the coupling was weak, the linewidth of the WG mode (measured employing an independent reference laser) ceased to depend on the coupling, and the Q factor was $\sim 10^9$.

The optical part of the apparatus (Fig. 1) consisted of an LT024MDO diode laser made by Sharp Co. ($\lambda = 780$ nm, output power 20 mW), a collimating objective ($N_A = 0.5$), an optical isolator with a controlled degree of suppression of a counterpropagating wave (maximum 30 dB), a focusing objective ($N_A = 0.4$), a coupling prism, a microsphere, and a photodetector. At maximum suppression of feedback, the diode laser operated on its own; modulation of the current then ensured tuning of the emission frequency. Under these conditions we observed a resonance of a WG mode (Fig. 2). The width of this resonance, which was not perturbed by optical feedback, was governed primarily by the diode laser linewidth and in our case was ~ 20 MHz. The Rayleigh scattering inside the silica microsphere generated a wave propagating in the opposite direction [5, 6]. Curve *1* in Fig. 2 was obtained with the counterpropagating wave

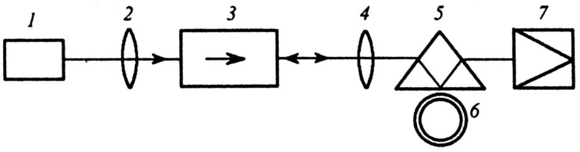

Figure 1. Schematic diagram of the apparatus: (*1*) diode laser; (*2*) collimating objective; (*3*) optical isolator; (*4*) focusing objective; (*5*) coupling-in prism; (*6*) microcavity with 'whispering gallery' modes; (*7*) photodiode.

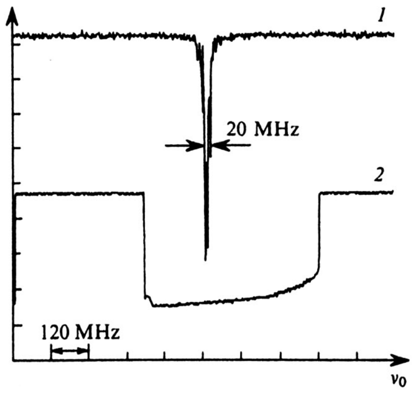

Figure 2. Demonstration of optical locking of a diode laser to a 'whispering gallery' mode: (*1*) resonance of microsphere 'whispering gallery' modes, unperturbed by optical feedback; (*2*) pulling of the diode laser frequency by resonant optical feedback.

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blocked by the isolator. When the degree of suppression by the isolator was reduced (by rotating one of the isolator polarisers), the counterpropagating wave reached the laser and this resulted in frequency locking (curve *2* in Fig. 2). An independent reference laser with an external cavity was used to measure the WG mode linewidth when the coupling corresponded to locking (curve *2* in Fig. 2) and the result was ~4 MHz. Comparison of curves *1* and *2* gave the ratio of the rate of frequency tuning when the pump current was varied in the absence of external coupling to the tuning rate under frequency-locking conditions: $S = (\mathrm{d}\nu_0/\mathrm{d}I)/(\mathrm{d}\nu_{\mathrm{ext}}/\mathrm{d}I) \geqslant 100$. For the phase noise, governing the width of the emission spectrum, with a uniform frequency distribution, the width of this spectrum should decrease by a factor exceeding $(1+S)^2$, i.e. the width should be less than 2 kHz.

The frequency-locking regime became stable when the gap between the laser and the microsphere was stabilised by an additional mirror (not shown in Fig. 1) with a piezoelectric ceramic (PZT) base [2], which made it possible to carry out direct linewidth measurements by a heterodyne method. The heterodyne was the reference laser with the external cavity. The spectra of the beat notes were recorded in the absence of optical feedback and for the optical coupling to the microsphere (Fig. 3). A comparison of these two spectra showed that the linewidth of the laser with the external microsphere decreased by more than two orders of magnitude and did not exceed 100 kHz. These measurements were carried out without taking any special measures to protect from the effects of vibrations and acoustic perturbations. Therefore, the beat-note spectra were additionally broadened by the technical noise. This noise was suppressed by heterodyne measurements of the emission linewidth of two lasers which were locked independently to two orthogonal WG modes of the microsphere. The coupling was provided by the same prism. Some of the technical noise was then correlated and the width of the beat-note spectrum became 20 kHz, which was quite close to the estimate given above.

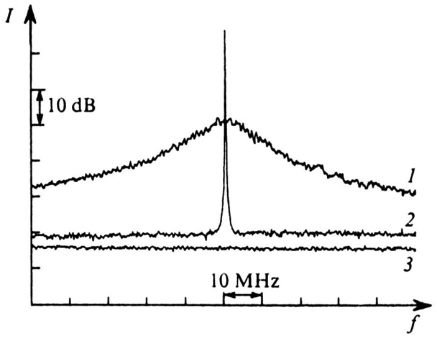

Figure 3. Spectra of the beat notes of the reference and investigated lasers in the absence of optical feedback (*1*) and in the presence of such feedback (*2*), and the photodetector signal in the absence of light, representing instrumental noise (*3*). Resolution $\Delta f = 100$ kHz; recording time 0.5; a video filter with a pass band 300 Hz was used.

In our experiments we made no attempt to utilise the small size of the microsphere in order to reduce the dimensions of the whole system. The problems of constructing miniature lasers with a linewidth of the order of 1 kHz will be discussed in a later communication, where we shall also provide a detailed description of the experiments (including that of the reference laser with two optical feedback loops), of the spectrum of the WG modes, and of the system locking two lasers with the aid of a microsphere.

It follows that resonant optical feedback provided by a microsphere with WG modes is an effective method for narrowing the diode laser linewidth and stabilising the emission frequency.

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