Injection locking of a red extended-cavity diode laser

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The radiation field of a high-power extended-cavity diode laser was phase locked by the field of a highly coherent master laser using an optical injection technique. The 20mW output beam of a slave laser of high mode quality acquired the spectral purity of the master laser.

Diode lasers are well appreciated as cheap, compact, and simple sources of coherent radiation in a variety of fields [1], including data communication or high-resolution laser spectroscopy. In the latter cases, a variety of applications exist where high spectral purity, high mode quality, and high power are needed at the same time. Especially in the red spectral range, solitary single (longitudinal and transverse) mode laser-diodes are so far capable of supplying only a few milliwatts of power, which is further reduced if they are used in an extended-cavity configuration to improve the spectral purity [2]. Conversely, there are high-power devices where the width of the active layer has been increased at the cost of a well defined transverse mode pattern. In the infrared spectral range, injection locking techniques [3] have been used to combine the good spectral and spatial properties of low-power singlemode lasers with high-power diode lasers or even diode laser arrays [4]. With broad area diode lasers, self-injection locking has improved the spectral purity, however, in the spatial domain, the laser remained multimode and astigmatic [5]. So far, in the visible range only, injection locking of small area diode lasers has produced several milliwatts of power with high spectral purity [6].

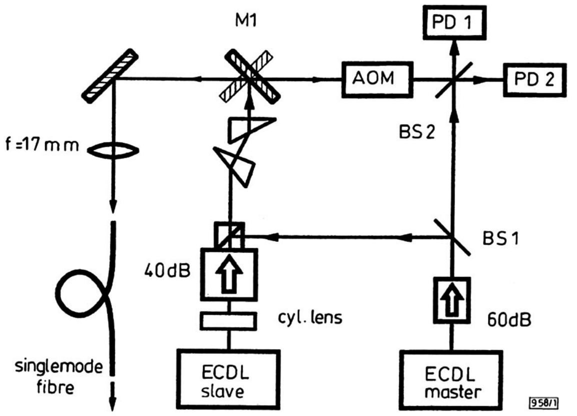

Fig. 1 *Experimental setup*

In this Letter, we report a master-slave configuration (see Fig. 1) capable of producing ~20mW of highly coherent radiation at 657 nm. A highly-coherent tuneable extended cavity diode laser (ECDL) system with optical- and fast electronic feedback loops was used as a master. This master ECDL comprised a Toshiba TOLD 9321 diode laser (DL) whose output facet was antireflection coated, with a residual reflection coefficient of $< 10^{-2}$ (as measured by the manufacturer). It differed from a similar system [2] by a Littman arrangement and an intracavity electro-optical crystal [7]. The electro-optical crystal served as a frequency-controlling element in closing the broadband (~MHz) feedback loop which uses an error signal from a high-Q reference cavity (not shown in Fig. 1) and consequently decreasing the linewidth of the ECDL from several hundreds of kHz to the sub kHz value, as measured by an independent spectroscopic experiment. Apart from this, the electro-optical crystal was inserted into the master cavity, decreasing the power of the laser by a factor of two in spite of the AR coating of the facets of the crystal, and worked as a negative lens with two different focal lengths in the two orthogonal planes.

A broad-stripe (100μm) diode laser (Philips CQL822/D) was used as a slave laser. According to the specifications, the solitary laser diode has reflection coefficients of the rear and front facets equal to 90 and 30%, respectively, and at 100mW output power, it oscillates in 3 to 10 transverse (lateral) modes and many longitudinal modes within the 2nm width of the spectrum envelope. In contrast to narrow-stripe red lasers, we found the injection locking technique to be ineffective with this broad-area laser, revealing still many lateral modes. Thus, for controlling spatial and spectral characteristics of the slave laser, the front facet of the laser diode was AR coated and was also set up as an ECDL (Littman) configuration using a cavity length of 12cm. The threshold current of the solitary LD in the slave laser was increased from 130 to 210mA by the AR coating.

The slave laser could be reliably operated in a single (longitudinal and fundamental transverse) mode only in a limited range of currents between ~175 and 265mA, yielding a maximum power of 20mW at 260mA. The behaviour of the slave laser differed from the typical behaviour of an ECDL, comprising a small area diode laser in such a way that it was necessary to use a high frequency-selective grating (1800lines/mm) to keep the fundamental transverse mode simultaneous with the high output power. To provide unidirectional coupling of the master and slave lasers, an optical isolator (–40dB) was placed between them (Fig. 1).

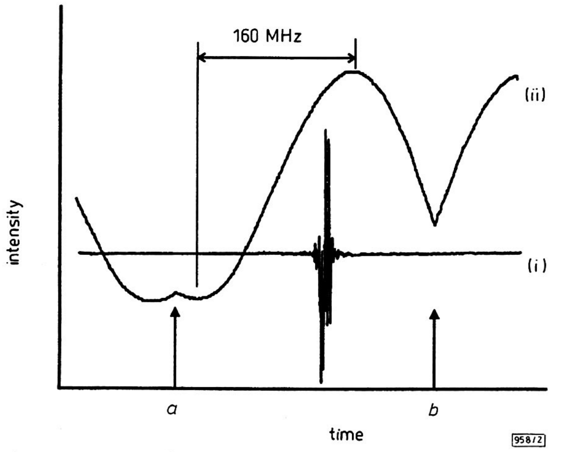

Fig. 2 *Beat-note signal recorded by photodiode PD 2 between master and slave lasers when master laser was ramped with blocked injection locking beam (curve (i)) and with injection locking beam (curve (ii))*

Slave laser loses lock close to points *a* and *b* where ramp voltage changes direction

To characterise the quality of the injection locking, the beam of the slave laser was redirected by mirror 1 (Fig. 1) to an acousto-optical modulator (AOM) and the diffracted beam (shifted by 80MHz) was superimposed on the radiation of the master laser with the help of beamsplitter BS2. One of the combined beams emerging from beamsplitter BS2 was detected with a fast photodiode (PD1) and the spectrum of this signal was displayed with a spectrum analyser. The second beam was detected by a photo diode (PD2) whose output was fed to a DC-coupled oscilloscope. Here, we observed a variation in the signal with the frequency of the master laser. When the injection path between the master and slave lasers was blocked and the master frequency was swept, the oscilloscope displayed no signal unless the frequency difference was small enough to fit into the bandpass of the oscilloscope (Fig. 2, curve (i)). The central part demonstrates the beating in the vicinity of zero frequency difference. This signal was convenient for final tuning of the laser. If some radiation of the master laser is injected into the active region of the slave laser, large variations in the signal occur. Because of the phase coherence between both lasers, the optical setup represents an unbalanced Mach-Zehnder-type interferometer where the radiation of the master laser behind beamsplitter BS1 propagates either directly to the beam splitter BS2 or via the optically locked slave laser. Owing to the length difference of the two paths of ΔL = 93cm, the free spectral range $FSR = c/\Delta L$ was 320MHz. The tuning of the frequency of the master laser and the change of phase due to the inherent properties of the injection locking both lead to an interference signal (curve (ii) of Fig. 2). By modulating the master laser we could determine when the slave lost lock from curves similar to curve (ii) of Fig. 2. We estimate the locking range to be 260MHz, neglecting the change of the phase inherent to the injection process. This value is smaller than the free spectral range of the slave laser of ~1GHz. This locking range was achieved with 0.9mW power of the master laser measured behind beamsplitter BS1, which left enough power for the servo system and diagnostics. It should be pointed out, however, that due to the limited coupling efficiency, only part of the 0.9mW is coupled into the active region of the slave.

To examine the stability of this lock, we used photodiode PD1. If the injection path was blocked, the beat note between the two free-running ECDLs, as measured by a spectrum analyser behind photodiode PD1, showed a width of ~100kHz. If the slave laser was injection-locked, the beat note spectrum became much narrower, with the width determined entirely by the bandpass of the analyser and servo bumps at ~30kHz. An estimate of the quality of the phase lock can be obtained from the ratio of the power contained in the carrier compared to the power remaining in the pedestal. In a similar way to [8], we found that the RMS phase difference of both laser fields is ~1/80rad, i.e. that > 99.97% of the power of the slave laser was contained in the carrier. It was surprising, however, that the servo bumps already occurred at 30kHz. The associated long time constant indicates that thermal effects are responsible.

Since the ellipticity of the slave laser beam was particularly large due to the high asymmetry of the active region, spatial filtering with a singlemode polarisation-preserving fibre was used. To decrease the losses by coupling the slave laser radiation to the fibre, we used a cylindrical lens (Fig. 1) and an anamorphotic pair of prisms. The resulting coupling efficiency into the optical fibre was 50%, indicating the high spatial quality of the laser beam.

In conclusion, we have optically phase-locked a broad-area diode laser in an ECDL configuration with an output power of up to 20mW of good spatial quality using < 1mW injected power. The residual RMS phase difference between both laser fields was < 1/80rad. This opens the way for applications in the field of high resolution spectroscopy or phase-coherent frequency synthesis which require diode laser wavelengths in the visible range that are no longer hampered by the limited power of solitary singlemode lasers.

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