Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 267 (2006) 455–463
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Modulation transfer characteristics of injection-locked diode lasers

M. Vainio [a,*], M. Merimaa [b], K. Nyholm [b]

[a] *Metrology Research Institute, Helsinki University of Technology, Finland*
[b] *Centre for Metrology and Accreditation (MIKES), P.O. Box 9, FI-02151 Espoo, Finland*

Received 7 March 2006; received in revised form 6 June 2006; accepted 19 June 2006

Abstract

In this paper, we investigate modulation transfer in an injection-locked diode laser when the master laser frequency or intensity is modulated. The modulation transfer properties of injection-locked diode lasers are shown to depend on frequency detuning between the master and slave lasers. This observation is of practical importance, since the laser frequencies are typically prone to ambient conditions. Also conversion of the master laser frequency modulation to slave laser intensity modulation is shown to be of importance if large frequency modulation amplitudes and small intensity modulation amplitudes of the master laser are used. On the other hand, the injection-locking technique is proved to be an effective way to suppress spurious intensity modulation in certain operational conditions.

Keywords: Diode laser; Modulation; Injection locking

1. Introduction

One of the advantages of semiconductor diode lasers compared to other type of lasers is their capability to be modulated at high frequencies (several GHz) by direct modulation of injection current. Direct modulation results to both intensity and frequency modulation on the laser output. However, in many applications it is desirable to obtain only pure frequency modulation or pure intensity modulation. For instance, pure frequency modulation is needed in certain absorption spectroscopy techniques. Such techniques are conventionally divided into two categories: In wavelength modulation (WM) spectroscopy the laser is modulated at a frequency lower than the width of the studied absorption line. The absorption profile converts the wavelength modulation to amplitude modulation, from which the approximate derivative of the profile can be deduced. If the modulation is done at higher frequencies, the technique is commonly referred to as frequency modulation (FM) spectroscopy. Both WM and FM spectroscopy are standard techniques e.g., in trace-gas detection and laser frequency stabilization.

In the most delicate applications of WM and FM spectroscopy the amplitude of frequency modulation must remain strictly constant and any distortion of the modulation must be minimized. Even more common requirement is that intensity modulation should be minimized. Spurious intensity modulation (or residual amplitude modulation, RAM) is detrimental as it leads to asymmetries and offset in the signal lines, thus shifting the line centers. It also carries the low-frequency noise to the signal frequency, which degrades the signal-to-noise ratio of the measurement [1,2]. The degree of spurious intensity modulation may be reduced e.g., by using an external modulator or by operating the diode laser in an external cavity and performing the modulation with a piezoelectric transducer (PZT). Naturally, these techniques are more complicated than direct current modulation, and in the case of PZT modulation the frequency modulation bandwidth is normally limited to a few kilohertz.

In addition to its other advantages in spectroscopy [3], diode laser injection locking has been used to reduce spurious intensity modulation both in FM spectroscopy [4] and

* Corresponding author. Current address: Laboratory of Physical Chemistry, P.O. Box 55, FIN-00014 University of Helsinki, Finland. Tel.: +358 50 5678620; fax: +358 9 19150279.
E-mail address: markku.vainio@helsinki.fi (M. Vainio).

0030-4018/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2006.06.054

WM spectroscopy [3]. Even if injection locking has been used in practice for reduction of intensity modulation, the capabilities and limitations of the technique have not been reported yet. In the ideal case, a slave laser, which is injected with light from a master laser, fully copies the spectral properties of the master laser. On the other hand, the slave laser output can be expected to be insensitive to small variations of the master laser intensity. However, as will be shown in this paper, these effects depend strongly on the injection locking parameters. Also conversion of the master laser frequency modulation to slave laser intensity modulation can have a significant effect on the total degree of intensity modulation at the slave laser output.

Extensive studies of current modulation properties of injection-locked diode lasers have been conducted, especially in view of optical communications. For instance, enhanced modulation bandwidth [5,6] and reduced nonlinear distortion [7,8] have been demonstrated. Recently, there has been some research on systems in which the master laser frequency or intensity is modulated, and the modulation is transferred to the injection-locked slave laser. Recent studies include theoretical models of the intensity modulation (IM) and frequency modulation (FM) transfer properties of injection-locked diode lasers [9–11] but also experimental data of the dependence of these phenomena on injection ratio and modulation frequency have been reported [11]. Transfer of the frequency modulation has been investigated also much earlier by Kobayashi and Kimura [12]. Another important effect, conversion of the master laser FM to slave laser IM has been discussed in Refs. [9,11]. However, the papers published so far do not cover all the important aspects. In particular, the effect of master–slave detuning has not been well covered, even if it is of essential importance in real systems that are affected by environmental conditions shifting the laser frequencies.

In this paper, the transfer of IM and FM in diode laser injection locking is studied in detail for various injection locking conditions. Our main motivation is to use the results for wavelength modulation spectroscopy in stabilization of a diode laser frequency on a molecular reference, and for that reason the experimental work only covers the frequency range below 50 kHz. The theoretical analysis is valid also for high modulation frequencies, and is applicable to FM spectroscopy and optical communications as well.

2. Theoretical model

Fig. 1 shows schematically the master–slave system discussed in this paper. Light from the master laser is injected into the slave laser through an optical isolator that blocks the reverse light path. Direct modulation of the master laser produces both IM and FM to the optical output of the laser. Master laser modulation can be transferred to intensity modulation of the slave laser in two different ways: through direct reproduction of the intensity modulation with certain efficiency, and through conversion of the master laser FM to slave laser IM (which is referred to as FM-to-IM conversion). Frequency modulation is transferred from master to slave laser.

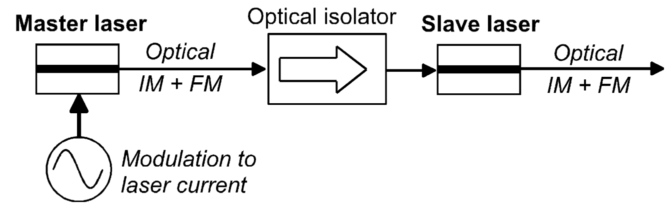

Fig. 1. Schematic of the master–slave system. Master laser is directly modulated and the modulation is transferred to the injection-locked slave laser.

We start analyzing the modulation transfer properties of the master–slave system from the rate equations for a single-mode diode laser. If the gain compression term, the spontaneous emission, and the Langevin noise terms are ignored, the rate equations for an injection-locked diode laser can be written as [10,13]

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = \left[G_0(N(t) - N_{\mathrm{th}}) + 2\mathrm{FSR}\sqrt{\frac{S_{\mathrm{inj}}(t)}{S(t)}}\cos(\phi_{\mathrm{inj}}(t) - \phi(t))\right]S(t), \tag{1}$$

$$\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = \frac{\alpha}{2}G_0(N(t) - N_{\mathrm{th}}) - 2\pi\Delta f + \mathrm{FSR}\sqrt{\frac{S_{\mathrm{inj}}(t)}{S(t)}}\sin(\phi_{\mathrm{inj}}(t) - \phi(t)), \tag{2}$$

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \frac{I(t)}{e} - \frac{N(t)}{\tau_N} - G_0(N(t) - N_{tr}). \tag{3}$$

In these rate equations, $S(t)$, $\phi(t)$, and $N(t)$ are the photon number, the phase, and the carrier number inside the slave laser cavity, respectively. G_0 is the gain coefficient, α is the linewidth enhancement factor, N_{tr} is the carrier number at transparency (zero gain), and N_{th} is the carrier number at threshold of the free-running slave laser. $I(t)$ denotes the slave laser bias current, e is the electron charge, and τ_N is the carrier lifetime. Injection rate is proportional to the slave laser free spectral range $\mathrm{FSR} = c/2L$, where c is the vacuum speed of light and L is the optical length of the cavity. Frequency detuning between the master and slave lasers is given by $\Delta f = f_{\mathrm{inj}} - f_{\mathrm{s}}$, where f_{inj} denotes the master laser frequency and f_{s} is the unperturbed cavity frequency of the slave laser (note that in this paper all the frequencies are given in Hz). The phase of the injected field is $\phi_{\mathrm{inj}}(t)$ and the number of injected photons inside the slave laser cavity is $S_{\mathrm{inj}}(t)$.

Many of the parameters defined above are relatively straightforward to determine also experimentally, even though the internal parameters of diode lasers are typically not very accurately known. When determining the injected photon number, the imperfect coupling between the master and slave lasers must be taken into account by including a