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Optics Communications 272 (2007) 217–220
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Frequency stabilization of multiple semiconductor lasers using digital feedback loop

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Received 15 August 2006; accepted 8 November 2006

Abstract

We propose and demonstrate a simple technique to stabilize the frequencies of multiple semiconductor lasers simultaneously using a Fabry–Perot etalon filter and a digital signal processing. Unlike other stabilization techniques, the proposed technique could stabilize DFB lasers using only one digital feedback control loop. The result shows that the proposed technique could maintain the frequency stability of 16 DFB lasers within ±150 MHz.

Keywords: Frequency stabilization; Semiconductor laser; Digital signal processing; Fabry–Perot filter

1. Introduction

Laser frequency stabilization in the 1.5-μm region has attracted a great deal of attention for optical fiber communication systems [1], optical fiber sensors [2], and high-resolution spectroscopy and metrology [3–5]. There have been many efforts to use absolute frequency reference lines for the stabilization of semiconductor lasers. For example, it has been reported that the frequency of a semiconductor laser could be stabilized by locking it to frequency reference sources such as Fabry–Perot cavities [6] and atomic/molecular spectral lines [7–9]. Most of these stabilization techniques utilize frequency-modulated (i.e., frequency-dithered) lasers and heterodyne detection based on an analog feedback loop [7]. In this paper, we propose and demonstrate a simple frequency stabilization technique using the digital feedback loop. This technique utilizes a Fabry–Perot etalon filter and a digital signal processing (DSP) board. To dither the optical frequency of a semiconductor laser, a small, distinct sinusoidal current was added to the injection current of a semiconductor laser. For the frequency stabilization, the laser output signal was detected after traversing a Fabry–Perot etalon filter, followed by sampling with an analog-to-digital (A/D) converter and numerical processing with Fast Fourier Transform (FFT). This procedure provided information on the first derivative of the transmission function of the Fabry–Perot etalon filter. Thus, the laser frequency could be anchored at the resonance frequency of the Fabry–Perot etalon filter by monitoring the Fourier-transformed data. It should be noted that, the operating frequencies of multiple semiconductor lasers could be stabilized easily by using only one digital feedback loop. To demonstrate the principle, we used the proposed technique to stabilize the frequencies of 16 semiconductor lasers (frequency spacing: ~100 GHz). The results showed that the frequencies of semiconductor lasers could be stabilized within ±150 MHz.

2. Experiments and results

Fig. 1 shows the experimental setup to stabilize the frequencies of 16 semiconductor lasers. Each DFB laser is slightly modulated by using a small sinusoidal current generated from the function generator in addition to the bias

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doi:10.1016/j.optcom.2006.11.030

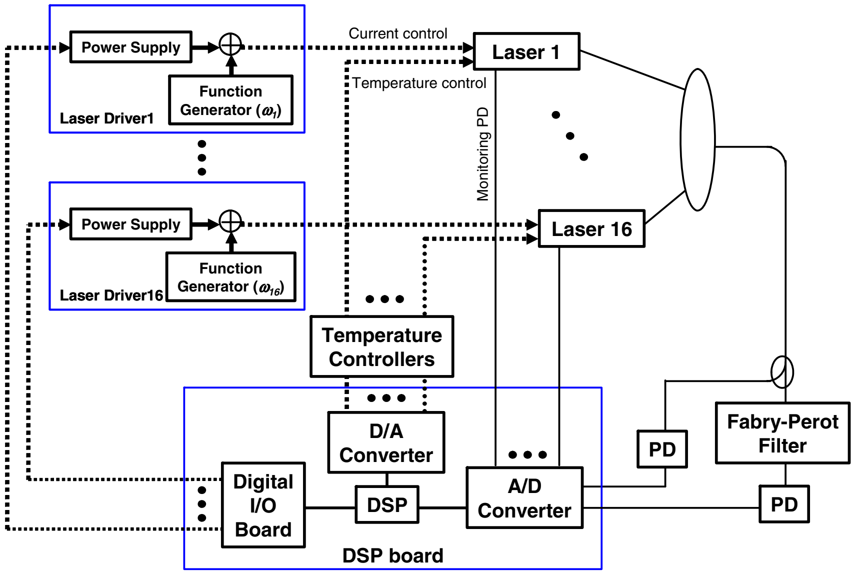

Fig. 1. Experimental setup to stabilize 16 DFB lasers simultaneously.

current from the power supply. Thus, the optical power and frequency of one DFB laser can be described as

$$\begin{aligned} P(t) &= P_0 + \Delta P_0 \sin(\omega_0 t) \\ v(t) &= v_0 + \Delta v_0 \sin(\omega_0 t + \phi_0) \end{aligned} \tag{1}$$

where P_0 is the average output power of the DFB laser, the ΔP_0 is the peak amplitude of the sinusoidal portion of the laser power, ω_0 is the angular modulation frequency, v_0 is the center frequency of the DFB laser, Δv_0 is the peak deviation of the laser frequency induced by the sinusoidal current, and ϕ_0 is the phase delay between the amplitude and frequency modulation, respectively [10]. When the frequency-modulated optical signal passes through the frequency reference (i.e., optical filter), the amplitude of optical signal can be modulated due to FM–AM conversion [11]. The output signal of frequency reference, $O(t)$, can be described as (we assumed the transmission characteristics of frequency reference is a slowly-varying function)

$$O(t) \approx \{T(v_0) - T'(v_0)\Delta v_0 \sin(\omega_0 t + \phi_0)\}\{P_0 + \Delta P_0 \sin(\omega_0 t)\} \tag{2}$$

where $T(v_0)$ and $T'(v_0)$ represent the transmission function of the frequency reference and its first derivative, respectively. In the experiment, we modulated each laser with a small sinusoidal current (±3 mA) ranging from 101 to 116 kHz with a separation of 1 kHz. When the DFB laser is modulated by a small injection current, then the optical frequency is modulated due to the temperature variation [10]. Basically, the optical frequency is modulated due to the thermal modulation of the active region of DFB laser when the injection current is modulated (modulation frequency: <1 MHz). The peak deviation of laser frequency, Δv_0, was measured to 0.16–0.4 GHz. The phase delay between amplitude and frequency modulations, ϕ_0, was measured to be about -0.2π when the dithering frequency was in ~100 kHz region. The average output power of each DFB laser was set to be 3 dBm. The temperature dependence of our DFB lasers was measured to be about −11.7 GHz/°C. Thus, the temperature of each DFB laser was controlled to be less than ±0.005 °C by using a temperature controller. The response time of the temperature controller was about 2 s. The output signals from 16 DFB lasers, spaced at about 100 GHz (@1.5 μm region), were combined using a star coupler, and divided into two parts. One part was directly sent to a photodetector and used to provide the reference phases for the digital signal processing (DSP) board, which consisted of an A/D converter, a microprocessor, a digital I/O board, and a D/A converter. The resolution and sampling frequency of the A/D converter were 12 bits and 250 kHz, respectively. The DSP board measured the amplitudes and phases of 16 tones simultaneously using the Fast Fourier Transform (FFT). The other part was first sent to the Fabry–Perot etalon filter which was used as a frequency reference as shown in Fig. 2a. We have constructed various solid etalons by coating both sides of 1.04-mm thick polished fused-silica glasses with seven layers of TiO_2/SiO_2. The Fabry–Perot etalon filter provides identical sets of absolute references without the need of frequency-locked lasers. The incident angle was adjusted to match the one resonant frequency of the etalon to the absolute reference [12]. The incident angle was fixed permanently after the adjustment was made. Fig. 2b shows the resonant frequencies of the etalon monitored directly by using a broadband light source and an optical spectrum analyzer. The free spectral range (FSR) of the etalon filter was 100 GHz. The temperature dependence of the resonant frequency of the quartz-based etalon is about −1 GHz/°C. The frequency stability of this filter was controlled to be better than ±50 MHz by using a temperature controller. It should be noted that, the temperature control loop of the Fabry–Perot etalon filter reduced