Optical Fiber Technology 31 (2016) 156–160

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

A recirculating delayed self-heterodyne method using a Mach–Zehnder modulator for kHz-linewidth measurement

Shuo Deng, Min Li, Hongyun Gao *, Yawen Dai

Department of Physics, Wuhan University of Technology, Wuhan 430070, China

ARTICLE INFO

Article history:
Received 15 April 2016
Revised 28 June 2016
Accepted 30 June 2016

Keywords:
Linewidth
Heterodyne
MZM

ABSTRACT

A laser linewidth measurement method which uses a Mach–Zehnder electro-optic modulator (MZM) is proposed in a loss-compensated recirculating delayed self-heterodyne interferometer (LC-RDSHI). Compared with the traditional acousto-optic modulator (AOM), the electro-optic modulator has the merits of broader bandwidth, lower insertion loss, higher extinction ratio and thus, a wider application. A theoretical analysis shows that the power spectrum curve of the novel measurement system is a Lorentzian line, which fits well with experiment. The linewidth is measured to be 137 ± 7 kHz at a frequency shift of 4 GHz. Measurement of a distributed feedback Bragg (DFB) laser has manifested that the linewidth broadens from 98.5 kHz to 137.4 kHz as the operating temperature changes by 16 °C. This work will allow investigation of narrow linewidth semiconductor and fiber laser stability.

1. Introduction

Narrow linewidth lasers have been extensively used in coherent optical communications, optical sensors and biophotonics [1–3]. Accurate laser linewidth measurement is essential for all these applications. Delayed self-heterodyne interferometry (DSHI) [4–7] is now a conventional method for laser linewidth measurement, first introduced by Okoshi [4] in 1980. In this method, incident light splits into two interferometer arms and light through an arm is delayed by passage through a single-mode fiber. Theoretical simulations and experimental results indicate the key prerequisite for accurate linewidth measurement [5] is that the time delay required is much longer than the coherence time of the laser and the delayed fiber length limits the accuracy of the DSHI technology.

Tesuchida [8] proposed an improvement to DSHI, which used a fiber ring to circulate the light in the around a loop and reduced the total fiber length in high precision linewidth measurements. However, the large transmission loss of the recirculating loop limits the maximal order of the detectable beat signal. In 1992, Dawson [9] reported an implementation of a loss-compensated recirculating delayed self-heterodyne interferometer (LC-RDSHI) which compensated the large loop loss by an erbium-doped fiber amplifier (EDFA) and led to a resolution below 1 kHz. Ming Han [10] proved that for direct linewidth measurement, the criteria was that the overall effective gain of the fiber loop must equal the square of coupling ratio. In 2012, Tsuchida [11] reported a method with optical filtering effectively suppresses spectrum distortion caused by high-order frequency shifting and showed the maximum number of loop passages is limited to about 9 (180 km delay) with the optical filtering technique.

An acousto-optic modulator (AOM), which introduces a specific frequency shift through single sideband modulation as in references [5,8–10,12], has a relatively narrow frequency shift range, in the region of several tens of MHz, high cost and less application for laboratory and industry. We propose a simple modified LC-RDSHI measurement system, which uses a Mach–Zehnder electro-optic modulator (MZM) operating at the carrier-suppressed double sideband modulation point instead of the AOM. Compared with AOM, the MZM has a much broader frequency shift range reaching Giga Hertz, lower driven power and insertion loss, broader bandwidth and higher extinction ratio. This measurement system can achieve a higher accuracy over a wider measurement range using the GHz spectral interval. As far as we know, few papers report a LC-RDSHI measurement system with an electro-optical modulator [13]. We start with a theoretical linewidth model, which is derived from the modulation function of the MZM, as well as the simulation results in Section 2. The experimental results in Section 3 demonstrate both experimental and theoretical curves are Lorentzian profile. We also discuss the dynamic linewidth of the distributed feedback Bragg (DFB) laser during a temperature tuning process and draw a conclusion on the relation of the laser linewidth and the working temperature.

* Corresponding author at: Wuhan University of Technology, Department of Physics, Nanhu Campus, Physics Ble. 510, Wuhan 430070, China.

E-mail address: ghyun@whut.edu.cn (H. Gao).

http://dx.doi.org/10.1016/j.yofte.2016.06.007
1068-5200/

2. Principles of the modified LC-RDSHI method

We use a MZM instead of an AOM in the new measurement schema as the frequency modulator, which introduces an appropriate frequency shift into LC-DSHI system. By properly setting the DC bias, the MZM operates at the carrier-suppressed double sideband modulation point. Assume the incident continuous wave has an expression

$$E(t) = E_0 \exp\{j[\omega_c t + \phi(t)]\} \tag{1}$$

where E_0, ω_c and $\phi(t)$ are the amplitude, angular frequency and phase fluctuation of the optical field, respectively. The output optical field of the single polarity MZM has the form as

$$E_{mod}(t) = E_0 \exp\{j[\omega_c t + \phi(t)]\} \cdot \sum_{n=-\infty}^{+\infty} J_n(\beta) \cdot \exp\left[jn\left(\omega_{RF} t + \frac{\pi}{2} + \phi_0\right)\right] \cdot \cos\left(\pi \cdot \frac{V_{bias}}{2V_\pi} + n \cdot \frac{\pi}{2}\right) \tag{2}$$

where ω_{RF} and ϕ_0 are the angular frequency and the initial phase of the RF driven signal, V_{bias} and V_π are the DC bias voltage and switching voltage of the MZM, $\beta = \pi V_m/2V_\pi$ is the modulation index, $J_n(\cdot)$ is the *nth*-order Bessel function of the first kind. The RF signal changes the refractive index of $LiNbO_3$ crystal, which creates an inequality in the push–pull phase shift between the two arms of the Mach–Zehnder interferometer. In this process, the influence of the line width shapes of the RF can be neglected because the single side-band (SSB) phase noise of the RF signal generator is −128 dBc/Hz (1 GHz, 20 kHz offset). The MZM operates at the optical carrier suppressed point under the condition of $\beta \ll 1$ and $V_{bias} = V_\pi$, the high order RF components ($n > 1$) corresponding to the *nth*-order Bessel function can be suppressed by choosing $\beta \ll 1$ and $V_{bias} = V_\pi$. Eq. (2) can be simplified as

$$\begin{aligned} E_{mod}(t) &= E_0 \exp\left\{j\left[\omega_c t + \frac{\pi}{2} + \phi(t)\right]\right\} \cdot J_1(\beta) \cdot (e^{j\omega_{RF} t} - e^{-j\omega_{RF} t}) \\ &= 2jE_0 \exp\left\{j\left[\omega_c t + \frac{\pi}{2} + \phi(t)\right]\right\} \cdot J_1(\beta) \cdot \sin(\omega_{RF} t) \end{aligned} \tag{3}$$

Thus, ω_{RF} is defined as the angular frequency deviation from the ω_c.

In a conventional DSHI system, the power spectral function can be written as [10,14–16]

$$\begin{aligned} S(\omega, \tau_d, \omega_{RF}) &= \frac{\alpha^2}{2} I_0^2 \frac{2/\tau_c}{(2/\tau_c)^2 + (\omega - \omega_{RF})^2} \\ &\times \left\{1 - e^{-2\tau_d/\tau_c}\left[\cos(\omega - \omega_{RF})\tau_d + \frac{2/\tau_c}{\omega - \omega_{RF}} \sin(\omega - \omega_{RF})\tau_d\right]\right\} \\ &+ \frac{\pi}{2} \alpha^2 I_0^2 e^{-2\tau_d/\tau_c} \delta(\omega - \omega_{RF}) \end{aligned} \tag{4}$$

where, τ_d is the fiber delayed time and τ_c is the laser coherence time. If $\tau_d \gg \tau_c$, the power spectrum function Eq. (4) can be simplified as [10,15]

$$S(\omega, \omega_{RF}) = \frac{\alpha^2}{2} I_0^2 \frac{2/\tau_c}{(2/\tau_c)^2 + (\omega - \omega_{RF})^2} \tag{5}$$

where, α is the coupling ratio of the coupler 1 (in Fig. 1), and I_0 is the incident light intensity. The power spectrum curve is Lorentzian in form and the full width at half maximum (FWHM) of the spectrum is calculated by $\Delta f_s = 2/\pi\tau_c$.

When light circulates inside the fiber loop, the LC-RDSHI system faces the influence of multiple interference. The spectral function of the *mth* order beat-note has an expression given as [10,12]

$$S(\omega) = \frac{\gamma^m}{(1-\alpha)^2} P(\omega) S_0(\omega, m\tau_0, m\omega_{RF}) \tag{6}$$

$$P(\omega) = \alpha + \frac{(1-\alpha)(\gamma^2 - \alpha)}{1 + \gamma^2 - 2\gamma\cos[(\omega + m\omega_{RF})\tau_0]}$$

where γ is the overall effective gain of the fiber loop, $P(\omega)$ is the modulation function and $S_0(\omega, m\tau_0, m\omega_{RF})$ is the power spectrum density function of the conventional DSHI method with the delayed time of $m\tau_0$ and angular frequency shift of $m\omega_{RF}$. Simulation results shown in Fig. 2 prove a power spectral curve of order $m = 2$ and $\omega_{RF} = 2$ GHz. The shape of the power spectral curve is Lorentzian in form.

3. Experiment results and discussion

3.1. Experimental details of the LC-RDSHI

An improved LC-RDSHI measurement using a MZM operating at a carrier-suppressed modulation point is shown in Fig. 1. We

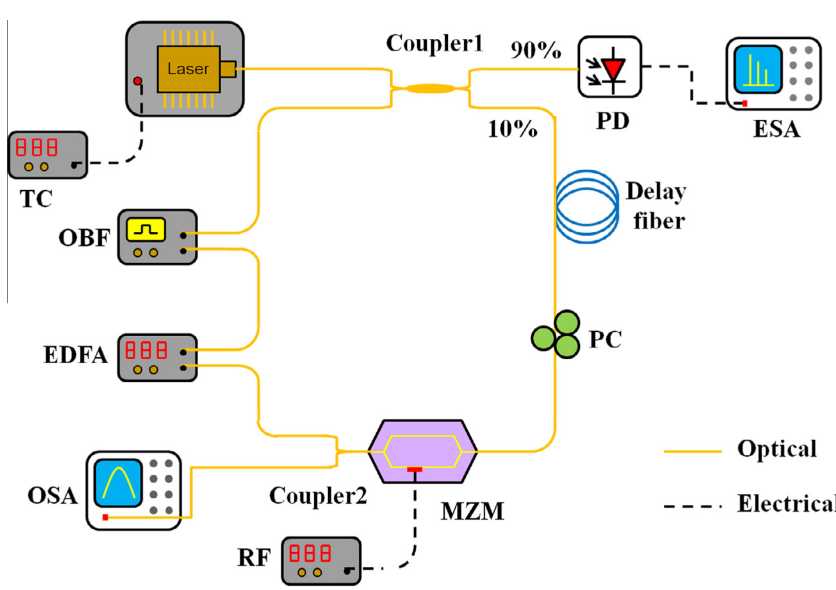

Fig. 1. Experiment setup of the proposed linewidth measurement method.