Optics Communications 325 (2014) 60–67

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Duplex self-mixing interference based on ultra-narrow linewidth fiber ring laser

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ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form
20 March 2014
Accepted 23 March 2014
Available online 3 April 2014

Keywords:
Fiber laser
Self-mixing
Laser sensor

ABSTRACT

A novel duplex self-mixing interference based on ultra-narrow linewidth fiber ring laser is investigated. Dense Wavelength Division Multiplexing (DWDM) is applied to add-drop the dual-channel vibration signal into the fiber laser. Meanwhile, the output power with optical feedback is theoretically deduced which can not only be interpreted by the well known expression of self-mixing interference but the combination of self-mixing interference and mode competition. Experimental results show that different movements of each channel detected from the dual-channel fiber laser self-mixing interference system are in good agreement with theoretical analysis. Furthermore, a novel system measuring 2-dimensional vibration is introduced in this paper and its potential application to self-mixing interference measurement system for high sensitivity, remote and multi-dimensional measurement is shown.

1. Introduction

Er^{3+} doped fiber (EDF) is effective for fiber ring lasers (FRLs) as it increases gain spectrum in both C-band and L-band [1–3]. Multi-wavelength fiber ring lasers (MFRLs) based on EDF appeal researchers for their potential applications in Dense-Wavelength-Division-Multiplexing (DWDM) optical communication systems, optical fiber sensors, surveillance and optical instrument testing due to their narrow linewidth, high power, low intensity noise, nearly diffraction limited beams, reliability, intrinsic safety, electromagnetic interference immunity, capability for remote control and low transmission loss [3–5]. Actually, EDF is not only an excellent gain medium but also an excellent saturable absorber [6–7,12] to narrow the fiber laser linewidth due to a super narrow band filter constructed by the un-pumped Erbium-doped fiber with high reflectivity fiber Bragg grating. The narrow linewidth is critical to coherence length limitation, high performance of self-mixing measurement system based on MFRLs that has rarely been reported so far.

Recently self-mixing interference (SMI) [8–14] has drawn much attention of researchers in optical sensor application due to its smart, easy alignment, high accuracy and reliability compared to the traditional heterodyne interference technologies, such as Michelson interference technology and Mach–Zehnder interference technology. SMI occurs when the light scattered by the object diffusing surface reenters the laser cavity. The feedback light modulates the gain and the frequency of the laser, so the amplitude and frequency of the object can be obtained through the demodulated processing circuit where one fringe shifting corresponds to a displacement of $\lambda/2$. Obviously novel multi-channel measurement could be realized in MFRL with ultra-narrow linewidth essential to remote, distributed, multi-parameter sensor by the SMI technique when a DWDM device is employed to split the lasing beam into multi-channel single wavelength light.

In this paper, we propose a novel dual-channel SMI vibrameter to obtain stable and high SNR self-mixing interference signals on the base of ultra-narrow linewidth dual wavelength ring erbium-doped fiber laser potentially applied to remote, distributed, multi-parameter sensors. In Section 2, we build a traditional three-mirror model to explain the SMI phenomena and propose the scheme of dual-channel vibrameter. In Section 3, the highly sensitive and stable results of vibration based on SMI are experimentally observed and theoretically analyzed by the combination of self-mixing interference and the model of Giles [15].

2. Principle

In this part a traditional three-mirror model [9,11] is introduced to the self-mixing vibrameter firstly. Both the gain and the

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http://dx.doi.org/10.1016/j.optcom.2014.03.070
0030-4018/

frequency of the laser are affected by the feedback light; hence, the modulated output power of the laser is related to external object vibration characteristics. Assuming one wavelength light would not interfere with the other lasing light in the dual-channel vibrameter investigated in the paper, the dual-channel vibration separately obtained as one wavelength self-mixing interference is analyzed. Fig. 1 shows a molding sketch of three-mirror laser lasing at single wavelength with an external cavity. r_1, r_2, and r_3 are reflection coefficients of the front (M_1), rear (M_2), and external (M_3) mirror respectively. L_{in} represents the length of the lasing cavity, while L_e is the distance from the rear mirror to the external mirror. In the process of solving the electric field equation and the phase condition based on the stationary stable laser oscillation, the equivalent cavity model is introduced in the traditional three-mirror model to obtain the results of self-mixing interference in which the rear (M_2) and external (M_3) mirrors are replaced by an equivalent mirror with a coupling coefficient of ζ [9]. In case of one-way reflection, $|r_3| \ll |r_2|$ and the external target is driven by a sinusoidal signal with the angular frequency of w_0 and amplitude of A; we can now derive expressions for the change of threshold gain and laser frequency with feedback.

$$\Delta v = \frac{C \ \sin(2\pi v \tau_e + \arctan \partial)}{2\pi \tau_{in}} \tag{1}$$

$$\Delta g = -\frac{\xi}{L_{in}} \cos(2\pi v \tau_e) \tag{2}$$

Eqs. (1) and (2) respectively, describe the change of laser frequency (ν) and threshold gain (g) resulting from steady-state amplitude and phase equations of lasing condition based on the self-mixing interference. Δg and $\Delta\nu$ represent the change of threshold gain and frequency in the laser with feedback. τ_{in} and τ_e are the time of a round-trip through inner cavity and external cavity, respectively. ∂ and C represent the line-width enhancement factor and the external feedback strength, respectively. Based on Eqs. (1) and (2) the laser intensity can be expressed as [11]

$$I = I_0(1 - \kappa \Delta g) \tag{3}$$

Here, κ is related to the operation parameters. From Eqs. (1)–(3), we can obtain the output power of the laser with feedback and Eq. (3) can be expressed as

$$I = I_0\left(1 + m \ \cos\left(4\pi v\left(\frac{L_e + A \ \cos(2\pi w_0 t)}{c}\right)\right)\right) \tag{4}$$

I_0 represents the output power without feedback. One fringe shifting corresponds to a displacement of $\lambda/2$; the frequency can be obtained by the period of SMI signal. Apparently we can easily calculate and obtain the vibration information through the self-mixing interference fringes in Eq. (4). Provided one wavelength light would not interfere with the other lasing light, the dual-channel vibration signal can be independently achieved as shown in the following equation by the three-mirror model:

$$I_i = I_{i0}\left(1 + m_i \ \cos\left(\frac{4\pi v(L_{ie} + A_i \ \cos(2\pi w_{i0} t))}{c}\right)\right) \tag{5}$$

where the subscript i denotes the related parameter of the i sensing channel. When DWDM is adopted to separate the multi-wavelength lasing light into multiple sensing channels, the multiple sensors can be realized with non-interference based on the self-mixing interference inside an MFRL.

3. Experimental results and discussion

3.1. The experimental setup of duplex SMI vibrameter based on dual-wavelength ultra-narrow linewidth fiber laser

In this section, the outstanding coherency source is applied to the dual-channel self-mixing interference to study the external target vibration. In the experimental setup schematically shown in Fig. 2, a duplex SMI vibrameter consists of a dual independent wavelength fiber ring laser (DFRL), a dual-channel light emission and collection system, two speakers with diffusing surfaces driven by two different signals of function generators and parallel processing circuits to process the SMI signals. To realize the DFRL, a DWDM is employed to divide dual-wavelength lasing light into two independent wavelength light sources. The dual-channel light emission and collection

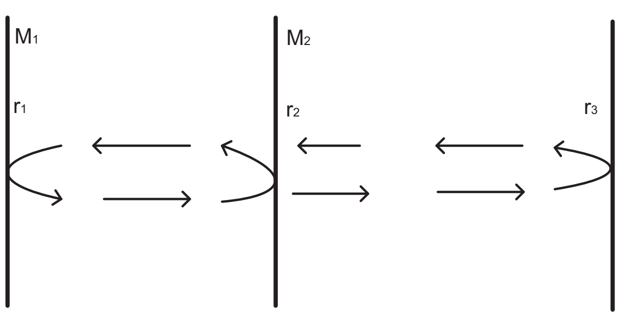

Fig. 1. Sketch of three-mirror model of self-mixing interference.

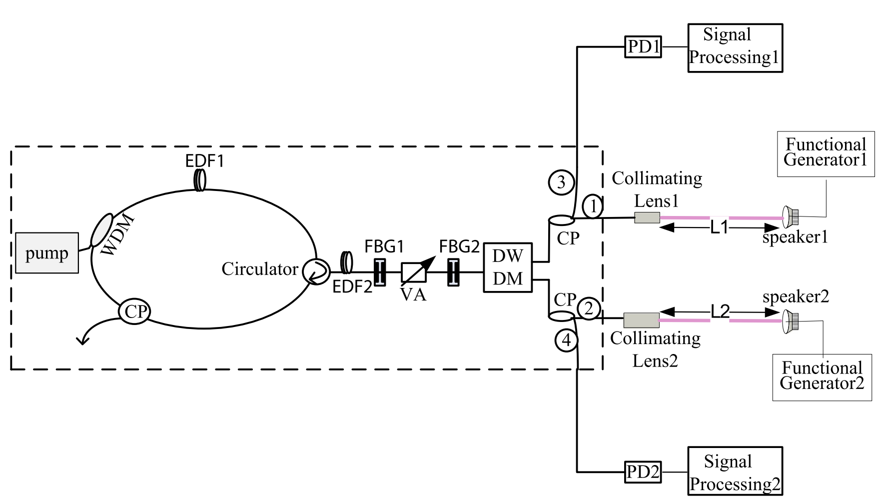

Fig. 2. Experiment setup of self-mixing vibrameter based on DFRL.