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Influence of external objects scattering property on self-mixing signal inside fiber laser

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ABSTRACT

The self-mixing sensor based on Er^{3+}–Yb^{3+} co-doped Distributed Bragg reflector fiber laser (EYDBR) has been demonstrated for detecting the effect of external objects scattering property on self-mixing signal. Results show that self-mixing interference inside fiber laser with short cavity length especially EYDBR fiber laser can keep high SNR with different types of scattering surfaces even the white print paper. Meanwhile, we have obtained a high and stable SNR at least 29.9 dB in measurements at incident angles smaller than 20°. In this way, the sensing system we demonstrate is suitable for vibration and displacement measurements, particularly for high-precision industrial measurements.

1. Introduction

The self-mixing phenomenon occurs when the laser beam is partially reflected from an external target and injected back into the laser cavity. Self-mixing effects within the laser create an output intensity modulation that is periodic in the optical phase difference induced by surface displacement or wavelength changes [1]. This modulation can be monitored on the output from the rear facet, using the monitor photodiode (PD) which is often found in the laser diode package. This phenomenon allows the laser to be used as the light source and the interferometer in one device, thus significantly reducing the cost and the complexity of the sensing system. Sensors based on this physical phenomenon have been designed for a large number of applications: absolute distance [2–4], displacement [5,6], velocity [7–9] and vibration [10,11] measurements.

Recently, considerable attention has been paid to the self-mixing effect of fiber lasers [11–14] due to low noise, compactness, resisting the electromagnetic interference, high slope efficiency, plentiful output wavelengths and high power sources. However, self-mixing interference is intrinsically very efficient only in single-frequency class B lasers [4], such as semi-conductor lasers: vertical cavity surface-emitting laser (VCSEL), distributed feedback (DFB) laser or Nd-doped microchip solid state lasers. In fact, the high sensitivity to optical feedback in a short laser cavity directly, which results from a short photon lifetime ($\tau_c = 10$ ns) compared to the emitting level lifetime ($\tau = 10$ ms). And a fiber laser with short cavity length has the superiority in comparison with the conventional one.

2. Theoretical part

As is well known, the optical feedback will modulate the laser power. When some back light scattered from external diffusely-reflecting reflector and into the laser cavity, then the self-mixing effect appears. The re-entering light carries with the information of external object then mixes with the inside light, and modulates the output signal of laser power. When the external reflector vibrates, the output power is notably modulated. The model commonly used to describe the dynamics of the self-mixing effect based on a three-mirror Fabry–Perot cavity model (Fig. 1) [15], a set of amplitude and phase equations with time-delayed feedback terms linking the phase and amplitude condition for the solitary laser.

The round trip phase with the laser cavity must be an integer multiple of 2π yielding the phase condition: $2\beta L + \phi_r = 2\pi m$, m = integer. Due to feedback, the emission frequency ν may change as well as the threshold gain, and thus the refractive index yielding a change of $\mu_e \nu$. And by using the effective refractive index $\mu_e = c\beta/(2\pi\mu)$, we can obtain the phase condition as:

$$\Delta\phi_L = \frac{\Delta(\mu_e \nu)4\pi L}{c} + \phi_r = \frac{4\pi L}{c}\left[\nu_0 \Delta\mu_e + \mu_e(\nu - \nu_0)\right] + \phi_r$$

The variation of the refractive index with varying carrier density is linked to gain variations via the parameter α, and also g must satisfy the amplitude condition with $g = g_c$. And introducing the round

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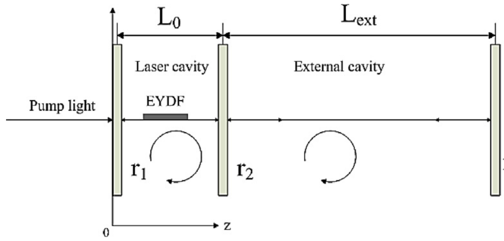

Fig. 1. Three cavity model of fiber laser with target.

trip delay $\tau_L = 2\overline{\mu_e}L/c$ of the solitary laser diode cavity, $\Delta\phi_L$ may be written as:

$$\Delta\phi_L = 2\pi\tau_L(\nu - \nu_0) + \xi\sqrt{1+\alpha^2}\sin(2\pi\nu\tau_{ext} + \arctan\alpha) \tag{1}$$

where τ_L is the round trip delay of the laser cavity; ν_0 is the emission frequency without feedback; ν is the emission frequency with feedback; $\xi = (1 - |r_2|^2)r_3/r_2$ denotes the feedback coupling coefficient, r_2 and r_3 is the reflection coefficients of the front facet of the laser and the external target respectively, α is the line width enhancement factor of fiber laser. τ_{ext} (=$2L_{ext}/c$) is the round trip delay of the external cavity, L_{ext} is the external cavity length.

According to stable situations, the phase condition characterized by $\Delta\phi_L = 0$ should be satisfied. The assumption of weak optical feedback results in an emitting power from the laser of:

$$p \approx p_0\left(1 + \zeta\cos\left(\frac{4\pi L_{ext}}{\lambda}\right)\right) \tag{2}$$

where p_0 denotes the total emitted power without considering the external feedback; $\zeta = 2\xi/\ln(R_1R_2)$ is related to the feedback coefficient ξ and the power reflectivities R_1 and R_2 of the laser facets, which is referred to here as the modulation index. Our goal in this work is to study self-mixing effect in fiber laser with short cavity length, in particular on the influence of external objects scattering property on self-mixing signal. In this case, as in the following writings, we have built a self-mixing interference vibration detecting system with all-fiberized configuration Er^{3+}–Yb^{3+} co-doped Distributed Bragg reflector (EYDBR) laser. Theoretical analyses based on three-mirror Fabry–Perot cavity model [15] were done and rightly justified the experimental results. All these results enrich the experimental and theoretical research in self-mixing effect, particularly in the different types of scattering surfaces and scattering angle influence.

3. Experimental setup and results

To investigate the performance of the proposed architecture we designed a system schematically shown in Fig. 2, based on an EYDBR fiber laser. The EYDBR fiber laser is composed of Wavelength Division Multiplexers1 (WDM1), Wavelength Division Multiplexers2 (WDM2), Fiber Bragg Gratings1 (FBG1: bandwidth 0.31 nm; diffraction efficiency reflectance 97% @ 1550.088 nm), Fiber Bragg Gratings2 (FBG2: bandwidth 0.21 nm; diffraction

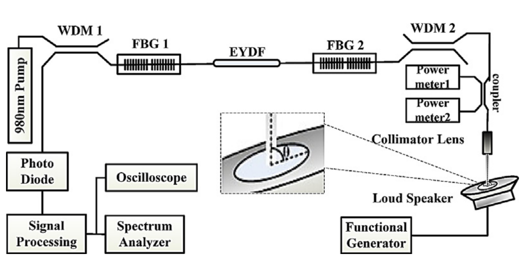

Fig. 2. Experimental setup for measuring the self-mixing signal based on EYDBR fiber laser.

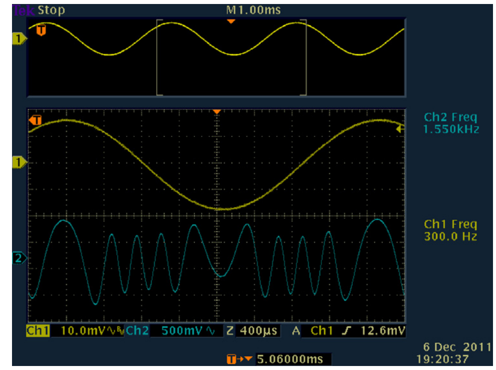

Fig. 3. Intensity modulation waveform of signal observed in the experiment.

efficiency reflectance 87% @ 1550.015 nm), 980 nm pump laser and a span of 4.2 cm length Er^{3+}–Yb^{3+} Co-doped Fiber (EYDF). The light emitting from the fiber laser is transferred by a collimator lens (OEFOC-202: Working Dist. 100 mm) to a piece of scattering film and then fed back to the fiber laser, interfering with the original field inside the cavity. Here, a scattering film is stuck on a block of mirror attached to the loud speaker which is driven by a function generator (Tektronix AFG3102). The self-mixing signal is finally exported from WDM1 and then detected by the PD followed by a signal processing circuit. The self-mixing signal processing circuit includes transimpedance amplifier, filters and further amplifier. Then the receiver is the transimpedance amplifier that is commonly used to convert the current generated by a photo elector into a voltage signal for further amplification. To reduce the effects of noise, a preamplifier is used to enlarge the signal strength to the main instrument without dramatically degrading the signal-to-noise ratio (SNR). Especially to remove unwanted frequency components from the signal and to enhance wanted ones, electronic filters are used which perform signal processing functions. A following amplifier makes the signal large enough to be observed. The output is observed by the oscilloscope, and can be analyzed to obtain the information of the loud speaker such as the frequency and amplitude of vibration. In Fig. 3, a picture taken from the oscilloscope is presented, which shows the PD current when the displacement of the target is a sinusoidal waveform. The upper trace in Fig. 3 is the signal applied to achieve the periodic target movement, and the resultant intensity modulation (lower trace) is the self-mixing interference signal observed. These results were obtained with pump current I_p = 114 mA, L_{ext} = 1 m, white printing paper as scattering surface. A sinusoidal signal was launched to loudspeaker with the frequency of 300 Hz and driving voltage of 137 mV. The amplitude of the loudspeaker is proportional to the driving voltage in small range of amplitude. As shown in Fig. 2, half wavelength movement of the feedback mirror will generate an undulation laser intensity fringe in the form of cosine or quasi-cosine waveform. It is clear that the self-mixing output shown in Fig. 3 is in good correspondence to that observed in the previous work of self-mixing effect with other types of laser [16–18].

For the further study external objects scattering property influence self-mixing signal, the corresponding electric signal which observed by PD was delivered to a radio-frequency spectrum analyzer. Experimental conditions are shown below: pump current I_p = 114 mA, L_{ext} = 1 m, driving frequency and amplitude is 580 Hz and 80 mV respectively, white printing paper as scattering surface. An example of the power spectrum of the modulated beam output is shown in Fig. 4. The vibration power spectrum highlights its vibration frequency (580 Hz), some of FM sidebands 1160 Hz, 1740 Hz and other frequencies. Because the self-mixing signals show a little instability, we adopt mean Signal to Noise Ratio (SNR) values of self-mixing signal by averaging SNR values every six times to describe