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Stabilizing DFB laser injection-locked to an external fiber-optic ring resonator

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Abstract: Self-injection locking to an external fiber cavity is an efficient technique enabling drastic linewidth narrowing and self-stabilization of semiconductor lasers. The main drawback of this technique is its high sensitivity to fluctuations of the configuration parameters and surroundings. In the proposed laser configuration, to the best our knowledge, for the first time the self-injection locking mechanism is used in conjunction with a simple active optoelectronic feedback, ensuring stable mode-hopping free laser operation in a single longitudinal mode. Locking to 4-m length fiber resonator causes a drastic narrowing of the DFB laser linewidth down to 2.8 kHz and a reduction of the laser phase noise by three orders of magnitude. We have explored key features of the laser dynamics with and without active feedback, revealing stability and tunability of the laser linewidth as an additional benefit of the proposed technique.

1. Introduction

Linewidth narrowing and stabilization of semiconductor laser light generation presents great research interest governed by a huge demand of compact cost-effective narrow-band laser sources with tunable coherency for many potential applications. Typical linewidths of free-running DFB semiconductor lasers range from a few to tens MHz. Self-injection locking of a laser through an external feedback is a promising technique for laser linewidth narrowing. To get the effect, a part of the optical radiation emitted by the laser is passed through a narrowband filter and returned back into the laser cavity thus providing a low laser threshold at the locked frequency [1,2]. Current progress in this topic is associated with the use of micro-cavities [3,4]. Alternative solutions based on long but relatively low-Q-factor fiber resonators are able to provide comparable linewidth narrowing by employing cost-effective laser systems built from standard telecom components. In particular, such solutions are of great interest for distributed Brillouin sensing, since the same fiber can serve as the laser cavity and the nonlinear medium to generate Brillouin shifted light [5–9]. Recently, we have demonstrated significant linewidth narrowing (>1000 times) of a conventional low-cost DFB laser locked to an external fiber optic ring resonator. Once locking, any slow change of the resonator mode frequency (due to temperature fluctuations, for example) leads to the same change of the laser frequency [9]. However, a stable laser operation into a single frequency mode is existing during time intervals limited to several seconds. Due to environment noise, the intervals of stable laser operation are interrupted by mode-hopping events. Although a precise stabilization of the laser diode current and temperature, combined with a precise thermal control of the fiber cavity, allow to extend these intervals to tens of minutes and even more (see [10], e.g., an impressive generation of sub-kHz linewidth with a rather complicated polarization maintaining (PM) laser configuration comprising a fiber

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Bragg grating Fabry-Perot cavity), no simple solution allowing to maintain self-injection locked operation of the DFB laser diode forever has been reported yet.

In this paper, we report on linewidth narrowing and stabilization of semiconductor DFB laser implementing the self-injection locking in conjunction with an active optoelectronic feedback circuit, controlled by a simple low-cost USB-DAQ card. Importantly, the fiber laser is built from standard SMF-28 (not PM as in [10]) components, has no thermal control of the fiber cavity, and employs a DFB laser diode powered by a standard driver. In this scheme, the laser linewidth narrowing is provided by self-injection-locking operation mode, whereas the active feedback just helps to keep the laser in this operation regime. Therefore, in terms of feedback bandwidth, complexity, and allocated memory, the used active feedback circuit is much less consuming than the Pound-Drever-Hall and Hansch-Couillaud systems commonly used with lasers [11,12]. We show as well that, in our laser configuration, the applied active feedback plays a second role granting control and tunability to the laser linewidth.

2. Experimental results and discussion

The experimental laser configuration is shown in Fig. 1(a). A DFB laser diode (MITSUBISHI FU-68PDF-V520M27B) operating at ~1534.85 nm and delivering ~5 mW is equipped with a 30dB optical isolator. The isolator eliminates the effects of back reflections and simultaneously limits the controllable value of the feedback signal returned to the DFB laser cavity. In order to implement the injection locking mechanism, the light emitted by the laser passes an optical circulator (OC) and is introduced through a coupler into a fiber ring resonator. The resonator is spliced from couplers C2 (95/5) and C3 (99/1) and comprises ~4 m of standard SMF-28 fiber. The coupler C3 redirects a part of the light circulating in the cavity (in CW direction) through the circulator (OC) back into the DFB laser providing a passive feedback for frequency locking. The spliced laser configuration is placed into a foam box to reduce the influence of the laboratory environment. No additional thermal control of the box is used.

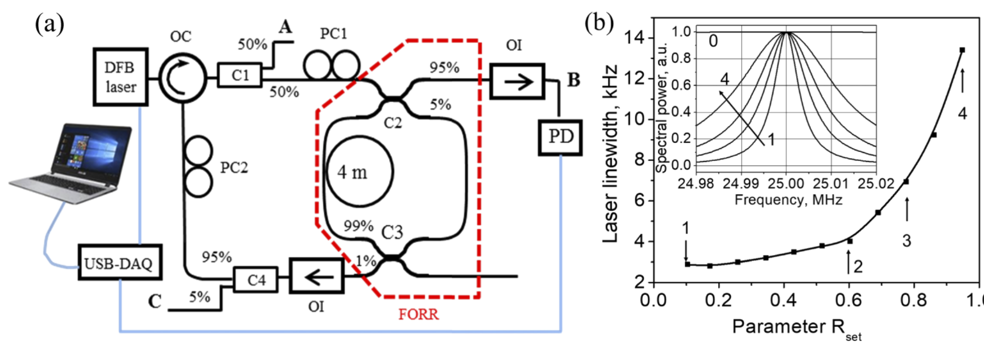

Fig. 1. (a) The experimental laser configuration; USB-DAQ - microcontroller, PD – photodetector, OC- optical circulator, PC – polarization controller, C – coupler, OI – optical isolator, FORR – fiber-optic ring resonator. (b) Laser linewidth as a function of the parameter R_{set}. Inset: the normalized self-heterodyne laser spectra (Lorentzian approximations) recorded in actively stabilized self-injection-locking (R_{set} = 0.08; 0.6; 0.77; 0.94, curves 1-4) and free-running (curve 0) laser regimes.

A delayed self-heterodyne technique has been employed to measure the linewidth of radiation emitted by the laser at different stabilization regimes. An all-fiber unbalanced Mach–Zehnder interferometer with a 35 km delay fiber and 25 MHz phase modulator equipped with a polarization controller is used for this purpose. The beat signal from the interferometer is detected by a ~5 GHz photodiode and analyzed by a RF spectrum analyzer. The laser full linewidth is a half of the full-width half-maximum (FWHM) of the Lorentzian fit of the measured RF spectrum [13].

Typical examples of Lorentzian fits to the self-heterodyne laser spectra are shown in Fig. 1(b), inset. When the passive feedback loop comprising the ring resonator (see, Fig. 1(a)) is open, the laser operates in a free-running regime, and its linewidth is estimated to be ~10 MHz. With a closed feedback loop, the laser starts to operate in self-injection-locking regime causing ~3000 times reduction of the linewidth down to a few kHz.

The minimal laser linewidth recorded in the experiment is ~2.8 kHz. In self-injection locking regime with passive feedback only, the laser linewidth maintains its minimal value during 1–100 s (depending on environmental noise level). Being driven by temperature fluctuations, it slowly walks within the range of 2.8–14 kHz (corresponding to ~10 MHz drift of the DFB laser frequency relative to the cavity resonance peak) until a mode-hopping event occurs. The efficiency of the laser linewidth narrowing is monitored by detecting the power reflected from or transmitted through the ring resonator (ports B and C, respectively). Both signals change synchronously in anti-phase. Indeed, a narrower laser linewidth corresponds to a lower power level P_B at port B and higher power level P_C at the port C. With the DFB laser operating in free-running regime, the power P_B gets the maximal value $P_{B\ max}$, whereas for the laser operating in self-injection-locking regime, the power P_B is lower, so the parameter $R = P_B \ / \ P_{B\ max} < 1$. When the DFB laser frequency matches the peak transmittance of the ring resonator, the laser linewidth is minimal and the parameter R gets its minimal value $R = R_{min}$. Any detuning of the laser frequency from its peak transmittance value increases both the laser linewidth and R. So, both frequency detuning and laser linewidth can be monitored by recording the parameter R.

Typical time-behavior of the reflected and transmitted powers (ports B and C, respectively) recorded in self-injection locking laser regime with passive feedback only are shown in Fig. 2(a). The observed behavior can be interpreted in terms of the frequency detuning, i.e., the laser frequency deviation relative the resonant transmission peak of the ring cavity [14]. The frequency detuning is caused by variations of ring resonator and DFB laser cavity lengths as a result of, for example, temperature effects. Following this detuning, the power parameter R varies in time, slowly walking between R_{min} and 1. Once getting the minimum value, the parameter R keeps it for a while as the laser is governed by the self-stabilization mechanism pulling the laser frequency toward the cavity resonant peak and thus providing the maximal feedback signal (i.e. minimal R). Physically, this means that, while the frequency detuning remains below a certain value (typically, ~10 MHz), the injection locking mechanism is able to stabilize lasing against temperature fluctuations or slow modulation of the DFB laser current. The stabilized laser frequency occurs to be locked to the cavity resonance peak, thus maintaining a constant value of the laser linewidth as well [14]. At some frequency detuning values, typically ~10 MHz, when the parameter R is increased approaching 1, the conditions for laser generation at two neighboring resonator peaks become equal and spontaneous noise provokes mode-hopping between two neighboring cavity modes. Obviously, mode hopping events disturb the laser stability.

The task assigned to the optoelectronic feedback circuit shown in Fig. 1(a) is to maintain the injection-locking laser operation (i.e. to keep the laser frequency detuning within the range available for self-stabilization) in order to avoid mode-hopping. For this purpose, the power reflected by the ring resonator (output B) is recorded by the photodetector and has to be maintained constant and linked to the set value R_{set}. From Fig. 2(a), it is seen that, due to environmental noise, R changes from 1 to its minimal value with a typical time constant τ_L~10 s. This value determines the maximal response time τ_F of the active stabilization circuit to correctly mitigate environmental noise, i.e., $\tau_F < \tau_L$. In our experiment, the active feedback loop operation is driven by a low-cost USB Multifunction DAQ (National Instrument NI USB-6009) connected to a PC. A deviation of the reflected power parameter R from the set value R_{set} is used as an error signal for the DAQ microcontroller that adjusts the laser operating frequency through a weak deviation of the laser diode current. With a change of the DAQ output voltage in the range 0 - 5 V, the additional laser diode current changes between ∓ 0.5 mA. Tuning the laser current within this

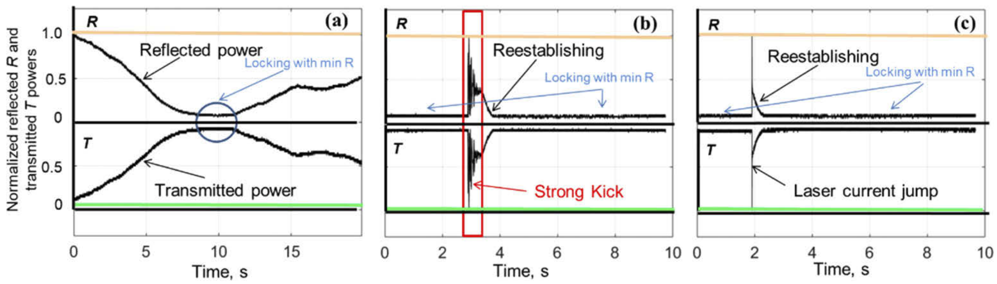

Fig. 2. Typical oscilloscope traces of normalized reflected and transmitted powers (black solid curves); (a) laser operation with optical feedback only; (b) optical and electronic feedbacks - responses on knock on the fiber ring; (c) optical and electronic feedbacks - responses on jump of laser diode current. Green, orange lines – free-running laser.

range provides a tuning of the free-running DFB laser frequency within ~1 GHz. When the optoelectronic feedback circuit maintains the power parameter R fixed to the set value R_{set}, it keeps locked both the frequency detuning and the laser linewidth. Curves 1-4 in Fig. 1(b) show the self-heterodyne laser spectra recorded with different set values R_{set}. With minimal $R_{set} = R_{min}$ ~0.08, the generated laser frequency coincides with one of the ring resonator transmission peaks and the laser linewidth gets its minimal value ~2.8 kHz. The corresponding traces of the reflected and transmitted powers recorded at ports B and C, respectively, are shown in Figs. 2(b) and 2(c). One can see flat traces that demonstrate perfect locking to constant levels with less than ~1% fluctuations. Note that, experimentally, we never reach $R = 0$ [15].

In order to identify the time constant associated with the feedback mechanism, we have measured the magnitude of the power parameter change in response to a short strong kick on the fiber configuration using a piezoelectric fiber stretcher attached to the ring. These measurements were made around a stable lasing point $R_{set} = R_{min}$. The response of the system on a rectangular voltage pulse applied to the stretcher is depicted in Fig. 2(b). When the fiber cavity is perturbed, it may exhibit a variety of dynamical behaviors. Clearly, the system behaves as a high-pass filter as high frequency acoustic perturbations cannot be compensated by the slow acting feedback. Following these perturbations, the power parameter (and the corresponding lasing frequency) shifts to a new value but then recoils and returns to the original point in an exponentially decaying manner. The typical time constant of the feedback mechanism is τ_F~0.3 s. Figure 2(c) shows the system response on a step change of the laser current forcing the DFB laser to switch to another mode (i.e. stimulating mode-hopping). One can see in this case that the system accepts this frequency change providing exponential relaxation to the new value with the same time constant of τ_F~0.3 s. In particular, such change of the laser current could be applied when the laser frequency deviation goes beyond the range of 1 GHz available for the laser stabilization with the low-cost USB DAQ used in this experiment. Tuning of the set power parameter R_{set} over the range from R_{min} toward 1 allows to change and stabilize the laser linewidth from the minimal (~2.8 kHz) to the maximal (~14 kHz) values. Therefore, avenue for tuning and controlling the laser linewidth is an additional benefit granted by the active feedback circuit.

To complete the picture, the noise performance of the self-injection-locked laser actively stabilized with different power parameters R_{set} and emitting narrow-band radiation of different linewidths has been characterized. Figure 3(a) depicts the phase noise power spectrum density (PSD) measured with a spectrum analyzer (Agilent N9320A) in the radio-frequency range of 10-100 kHz. Following the method described in [16–18], the PSDs have been obtained by employing self-heterodyne technique using a fiber unbalanced Mach–Zehnder interferometer with a 1.3 km delay fiber (5.76 μs) and 20 MHz frequency shifter. One can see that the maximal

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PSD levels are -25 dBc/Hz at 10 kHz frequency offset from carrier and -62 dBc/Hz at 100 kHz frequency offset from carrier for the laser operating with the linewidth of ~13 kHz ($R_{\text{set}} = 0.9$). PSD levels for the laser operating with the linewidth of ~2.8 kHz ($R_{\text{set}} = 0.08$) are lower by ~(25-27) dB over the same range. Note also that the spectrum range has been selected well above the active feedback circuit bandwidth thus avoiding its influence on the results [17].

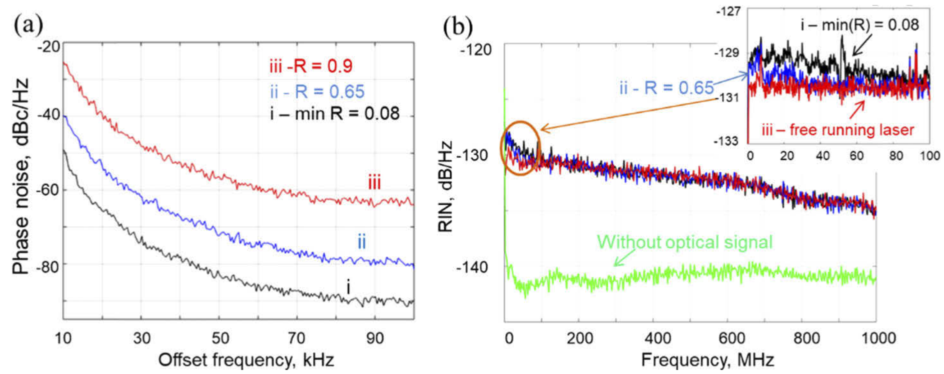

Fig. 3. (a) Phase noise of the stabilized DFB laser at different R_{set}. (b) Relative intensity noise (RIN) of the DFB laser at $R_{set} = 0.08$ (i); 0.65 (ii) and in free running (iii).

Figure 3(b) presents the relative intensity noise (RIN) spectrum measured with a low noise preamplifier (1 GHz bandwidth) and Agilent N9320A RF analyzer. All recorded RIN curves are well below -120 dB/Hz and do not depend significantly on the laser linewidth. Only a slight difference in the RIN values is observed at frequencies below 100 MHz. The reported noise laser characteristics are typical for fiber lasers based on injection locking [19–20].

It is worth to note that, for stabilized laser operation in self-injection locking regime, the laser frequency is strongly locked to the cavity resonance peak. Therefore, the laser frequency drift is mainly determined by the drift of the ring cavity resonance frequency affected by the environmental noise. The laser long-term frequency drift, determined by the thermal stability of the external ring cavity, is estimated to be ~10 MHz/min [6]. This value is in good agreement with the value measured earlier [10] under similar conditions. Similar to [10], our spliced laser configuration is placed into a foam box to reduce the influence of the laboratory environment. No additional thermal control or any particular vibration and acoustics insulation protections are used. Note, however, that the minimal laser linewidth of ~2.8 kHz achieved in our experiment is ~3 times larger than that the one reported in [10]. It is explained by a rather low value of the feedback signal due to the ~30 dB built-in isolator of the DFB laser. We believe that the use of DFB diode laser packaged without an internal isolator will allow to optimize the feedback signal level (like it is done in [10]) to decrease the laser linewidth down to sub kilohertz level in future experiments. Besides, the use of fully PM configuration should improve the laser stability with respect to its current characteristics presented in Figs. 2(b) and 2(c).

3. Conclusion

In conclusion, we have implemented an active feedback loop based on a low-cost USB-DAQ to stabilize an optical source using a DFB laser coupled to an all-fiber ring cavity and working in self-injection-locked mode. This configuration provides mode-hopping free laser operation at a single longitudinal mode. Good agreement is found between the experimentally observed and numerically simulated features of the laser dynamics reported earlier [14]. These results enhance our understanding of the self-injection-locking mechanism in semiconductor lasers and open up new possibilities for manipulating and controlling their properties. In particular, new ability to control and tune the laser linewidth is attractive for many laser applications, including high-resolution spectroscopy, phase coherent optical communications, distributed fiber optics sensing, coherent optical spectrum analyzer, and microwave photonics.

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Disclosures

The authors declare no conflicts of interest.

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