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Active stabilization of the DFB laser injection-locked to an external fiber-optic ring resonator

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ABSTRACT

Spectrally pure lasers are the heart of precision high-end scientific and commercial applications. Self-injection locking of a DFB laser through an external feedback is one of the most promising mechanisms for the laser line narrowing. To provide the effect, a part of the optical radiation emitted by the laser is returned back into the laser cavity. This relatively simple technique allows to design cost-effective narrow-band laser sources based on standard laser diodes making them an attractive solution in comparison with conventional laser systems based on an active feedback. Recently, we have demonstrated significant line narrowing (~1000 times) of a conventional low-cost DFB laser locked to an external fiber optic ring resonator. Once locking, any slow change of resonator mode frequency (due to temperature fluctuations, for example) leads to a simultaneous change of the laser generation frequency. However, in real conditions, in the presence of environment noise the stable laser operation in a single longitudinal mode occurs within a time interval limited to several seconds. These intervals are interrupted by short-time jumps in the lasing intensity caused by laser mode-hopping. Here, we report on linewidth narrowing and stabilization of semiconductor DFB laser implementing the self-injection locking in conjugation with an active optoelectronic feedback controlled by the simplest low-cost USB-DAQ card. In this assemble, the principle laser linewidth narrowing is provided by the self-injection-locking mechanism, whereas the applied active feedback helps to maintain this passive stabilization regime. Therefore, in terms of the feedback bandwidth, complexity, and allocated memory the proposed combined solution is much less consuming than active stabilization schemes based on the Pound-Drever-Hall (PDH) and Hansch-Couillaud methods commonly used with fiber lasers. Moreover, we will show that the active optoelectronic feedback which is initially implemented for better laser stabilization plays a second role granting control and tunability to laser linewidth.

Keywords: Distributed sensing; phase-OTDR; semiconductor laser; injection locking.

1. INTRODUCTION

Compact cost-effective laser sources with tunable coherency are of the great demand for a number of potential applications [1-9]. Linewidth narrowing and stabilization of semiconductor laser light generation are of topical research interest. Among them are high-resolution spectroscopy, phase-coherent optical communications, microwave photonics, coherent optical spectrum analyzer, and distributed fiber optics sensing [10-24]. Linewidths of free-running DFB semiconductor lasers typically range from a few MHz. Self-injection locking to an external fiber cavity is an efficient technique enabling drastic linewidth narrowing and self-stabilization of semiconductor lasers. To provide the effect, a part of the optical radiation emitted by the laser is returned back into the laser cavity thus decreasing the laser threshold at the locked frequency [25]. This relatively simple technique allows to design cost-effective narrow-band laser sources based on standard laser diodes making them an attractive solution in comparison with conventional laser systems based on active feedback. Traditionally, self-injection locking laser configuration comprises a narrow bandpass optical filter inside a weak

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feedback loop [26]. Current progress in this topic is associated with the use of micro-cavity techniques [27,28]. Employing optical whispering-gallery-mode resonators the linewidth of the semiconductor laser could be decreased down to sub-kHz range in a compact and robust configuration. However, the external cavities used in such systems possessing huge Q-factors ($\sim 10^{11}$) are not flexible for adjustment and require rather complicate coupling of fiber and non-fiber elements. Alternatively, all-fiber cavity solution based on long but relatively low-Q-factor fiber-based resonators is able to provide comparable semiconductor laser line narrowing employing low-cost fiber configuration built from standard telecom components [29-33]. In particular, such solutions are of great interest for RF-generation and Brillouin distributed sensing, the same fiber cavity can serve as a nonlinear medium to generate Brillouin frequency-shifted light [34-53]. Recently, we have demonstrated significant line narrowing (more than 1000 times) of a conventional low-cost DFB laser locked to an external fiber optic ring resonator [33]. Once locking, any slow change of interferometer mode frequency (due to temperature fluctuations, for example) leads to a simultaneous change of the laser generation frequency.

The main drawback of this technique is its high sensitivity to fluctuations of the configuration parameters and surroundings. Commonly, self-stabilization of the laser operation through injection locking is supported only within a limited range of the laser frequency deviations, typically tens of MHz [30]. Beyond this range even a minuscule fluctuation in the ambient parameters can destabilize lasing causing mode-hopping. As a result, stable laser operation intervals are interrupted by short-time jumps in the lasing intensity caused by laser mode-hopping [33]. Although the precise stabilization of laser pump current and temperature of fiber configuration allows increasing these intervals up to tens of minutes, no simple means permanently stabilizing laser operation in a single longitudinal mode have been reported yet. Rare mode-hopping events still interrupt frequency locking making many practical laser applications questionable.

In this paper, we have used the self-injection locking mechanism in conjugation with an additional active optoelectronic feedback extending the range of the laser self-stabilization over ~1GHz [54]. Since the optoelectronic feedback loop just helps to maintain the regime of passive self-injection-locking that makes the major contribution to the laser linewidth narrowing, in terms of the feedback bandwidth, complexity, allocated PC memory the proposed combined solution is much less consuming than the optoelectronic feedback circuits commonly used with single-frequency fiber lasers [55,56]. We have explored key features of the laser operation with and without the active feedback, in particular, demonstrating a control and tuning of the laser generation linewidth.

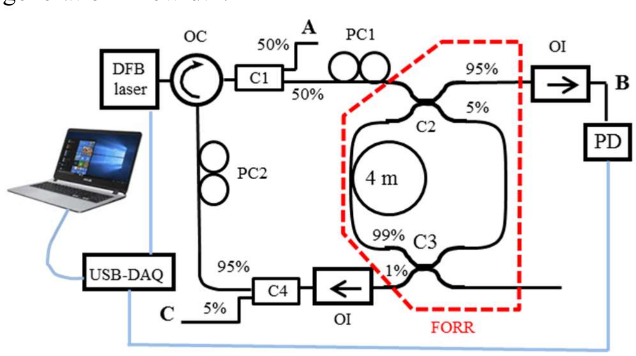

Fig. 1. The experimental laser configuration; USB-DAQ - microcontroller, PD – photodetector, OC- optical circulator, PC – polarization controller, C – coupler, OI – optical isolator, FORR – fiber-optic ring resonator.

2. EXPERIMENTAL CONFIGURATION

The experimental configuration of a semiconductor DFB laser coupled to a fiber-optic ring resonator is shown in Fig.1. The standard laser diode (MITSUBISHI FU-68PDF-V520M27B) operating at wavelength near 1534.85 nm with the output power of ~5mW is supplied by a built-in optical isolator attenuating the power of backward radiation by ~30 dB. The built-in optical isolator eliminates the effects of uncontrollable back reflections and simultaneously reduces the value of a controllable feedback power obtained from the external fiber optic ring resonator. 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 C2 into a ring resonator. The ring resonator is spliced from couplers C2 (95/5) and C3 (99/1) and comprises totally ~4m length of standard SMF-28 fiber. The coupler C3 redirects a part of the light circulating in the cavity (in CW direction) through circulator (OC) back into the DFB laser providing a passive feedback for frequency locked laser operation. 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 disbalanced Mach–Zehnder interferometer with a 35 km delay fiber and 25 MHz phase modulator supplied by polarization controller is used for this purpose [57]. The beat signal from the interferometer is detected by a ~5 GHz photodiode and RF spectrum analyzer.

3. LASER DYNAMICS WITHOUT AN ACTIVE FEEDBACK

Typical examples of the resultant spectra are shown in Fig.2 (inset). When the passive feedback loop, comprising the ring resonator (see, Fig.1), is open, the laser operates in a free-running regime. Its full linewidth at half-maximum is estimated to be ~10 MHz. With built-up feedback loop self-injection-locking regime is established and followed by a drastic (~3000 times) reduction of the laser 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 1–100s (depending on environment noise level). The rest time it slowly walks within the range of 2.8 – 14 kHz until mode-hopping event occurs. The efficiency of laser linewidth narrowing could be monitored by detecting the reflected power at port B or transmitted through the ring resonator power at port C. Both power signals are synchronized, the transmitted power changes in anti-phase with the reflected power. With the laser operating in free-lasing regime the power P_B gets the maximal value $P_{B\max}$. 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 generated laser frequency coincides with one of the ring resonator transmittance peak, the laser linewidth is minimal and the parameter R gets its minimal value $R = R_{\min}$. Any detuning of the laser frequency from the cavity resonant peak frequency increases both the laser linewidth and the parameter R . Therefore, both detuning of the laser frequency from the cavity resonant frequency and laser linewidth could be monitored by recording R .

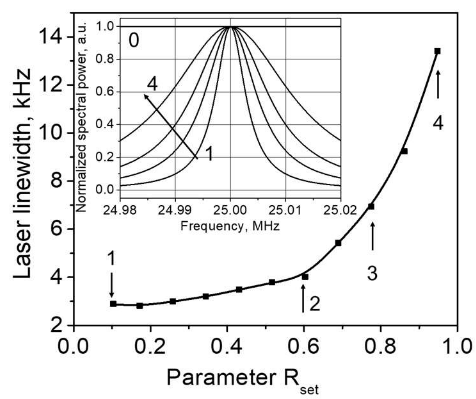

Fig. 2 Laser linewidth as a function of the parameter R_{set} . Inset: the normalized self-heterodyne laser spectra (Lorentzian approximations) recorded in actively stabilized self-injection-locking ($R_{set} = 0.1; 0.6; \ 0.77; 0.94$, curves 1-4) and free-running (curve 0) laser regimes.

Typical time-behavior of the reflected and transmitted powers recorded at ports B and C, respectively, in self-injection locking regime with passive feedback only are shown by solid black curves in Fig. 3a. In accordance with Ref. 30 the observed behavior could be interpreted in terms of the deviation of the laser frequency from the cavity resonant frequency peak referred to as the frequency detuning. The frequency detuning can be caused by various reasons such as variations in ring resonator length, instabilities of the laser current and/or temperature and etc. Following this detuning, the power parameter R varies in time slowly in the range between $R = R_{\min}$ and $R = 1$.

Slow changes of the frequency detuning correspond to the changes of the laser generation frequency in respect to the position of the ring resonator transmittance peak. Once getting the minimum value the parameter R keeps it for a while due to self-stabilization of the laser frequency governed by injection-locking mechanism that is always trying to maximize the feedback signal (i.e. to minimize the parameter R).
Physically, this means that with temperature fluctuations or slow modulation of the operating currents within a certain frequency deviation range the injection locking mechanism is able to stabilize lasing at the frequency strongly locked to the ring resonator transmission spectral peak maintaining as well the linewidth and shape of the laser generation line.

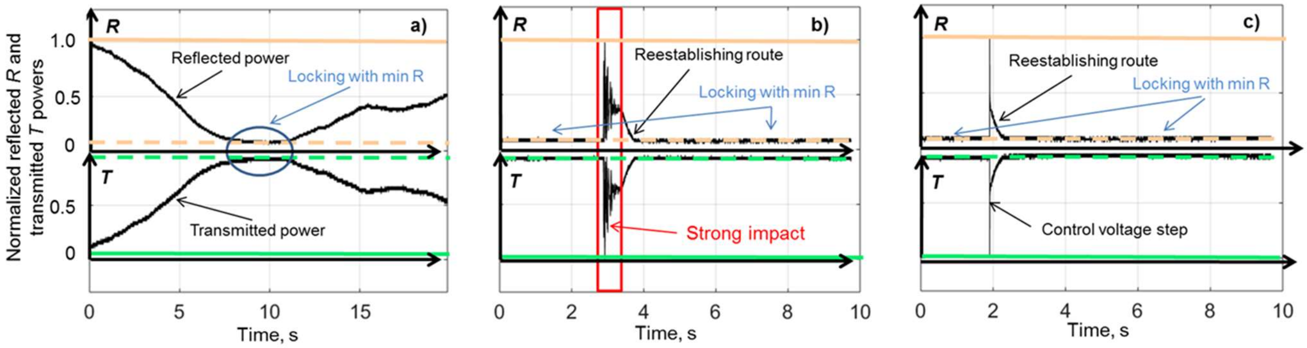

Fig. 3. Solid black curves -typical oscilloscopic traces of normalized reflected and transmitted powers. Solid green and red lines – levels for free-running laser without optical and electronic feedbacks. Dotted green and red lines – levels for laser locking with minimal R; a) laser operation with optical 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.

According to Ref.30 the laser generation linewidth is determined by the shape of the ‘‘potential well’’ associated with the resonator transmission peak directing the laser operation. At some frequency detuning values, typically ~10 MHz, when the parameter R is increased approaching unity the conditions for laser generation at two neighboring resonator peaks becomes equal and spontaneous noise provokes mode-hopping between two ring-resonator modes leading to a sudden change of the laser generation frequency by a value equal to the resonator free spectral range FSR. Obviously, such stochastic mode hopping disturbs the laser stability and impairs its performance characteristics. Therefore, in order to achieve a stable laser operation, the system temperature and laser operation currents should be stabilized at the levels ensuring the frequency detuning within the range corresponding to self-injection-locking. It is technically achievable, but rather cost consumable task.

4. LASER DYNAMICS WITH AN ACTIVE FEEDBACK

The task assigned to the optoelectronic feedback loop shown in Fig.1 is to maintain the injection-locking laser operation (i.e. to keep the laser frequency detuning within the stable operation range) avoiding mode-hopping. For this purpose, the power reflected by the ring resonator (output B) and recorded by the photodetector has to be maintained constant and equal to the set power level. The typical rate of the power parameter R slow changes shown in Fig.3(a, curve 1), the unity per 10 s, determines the minimal requirement to the response time of an active stabilization circuit. In our experiment the active feedback loop operation is driven by a low-cost USB Multifunction DAQ (National Instrument NI USB-6009) connected to 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 could adjust 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 - 5V the additional laser diode current changes between $\mp$ 0.5 mA. Such current deviation can tune the free-running DFB laser frequency within ~1GHz range. When the optoelectronic feedback loop maintains the power parameter R fixed to the set value R_{set}, it keeps locked both the frequency deviation of the laser from the resonant ring resonator frequency peak and the laser linewidth. Curves 1-4 in Fig.2 show the self-heterodyne laser spectra recorded with different set values R_{set}. With minimal $R_{set} = R_{\min} \sim 0.1$ the generated laser frequency coincides with one of the ring resonator peaks and the laser linewidth gets minimal value ~2.9 kHz. The corresponding traces of the reflected and transmitted powers recorded at ports B and C are shown in Fig.3 (b,c). One can see, that both dependences demonstrate perfect locking to the constant levels with less than ~1% fluctuations. Experimentally, we never reach R = 0 in spite of meticulous polarization adjustment. We suppose that this effect is due to unwanted polarization coupling and small birefringence inside FORR that make impossible to get a comprehensive destructive interference [33].

In order to identify the time constant associated with the applied feedback mechanism, we have measured the magnitude of the power parameter R change in response to a short strong kick on the fiber configuration using a piezoelectric fiber stretcher attached to the ring. These measurements were around a stable lasing point $R_{set} = R_{\min}$. The response of the system on a triangular voltage pulse applied to the stretcher is depicted in Fig. 3(b). Following these perturbations, the power parameter (and the corresponding lasing frequency) shifts to a new value but then recoils and returns to the $R_{set} = R_{\min}$ in an exponentially decaying manner. The typical time constant of the feedback mechanism is ~0.3 s. Fig.3(c) shows a system response on a step change of the laser current forcing the DFB laser to switch the generated mode (i.e. stimulating mode-hopping). One can see that in this case the system accepts this frequency change providing exponential relaxation to the new value with the same time constant of ~0.3s. In particular, such change of the laser current could be applied when the laser frequency deviation goes beyond the range of ~1GHz available for laser stabilization with the low-cost USB DAQ used in the 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 (~2.9 kHz) to maximal (~20 kHz) values, i.e. by one order of magnitude. Therefore, avenue for tuning and controlling the laser generation linewidth is an additional benefit granted by the use of the low-cost active feedback circuit.

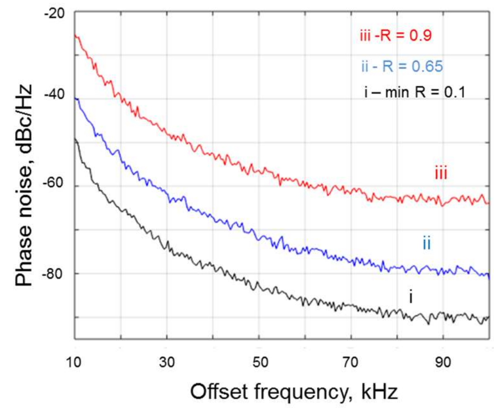

Fig. 4. Spectrum density (PSD) of the stabilized DFB laser phase noise at different R_{set}

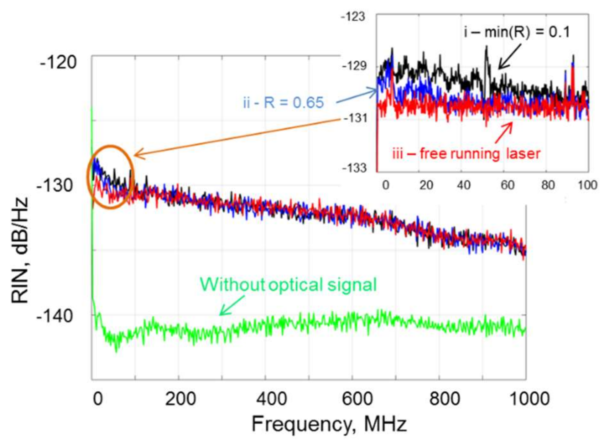

Fig. 5. RIN of the DFB laser at different $R_{set} = 0.1(i); 0.65(ii)$ and free running regime (iii).

5. LASER NOISE PERFORMANCE

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. Fig. 4 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 [58-60] the presented data have been obtained employing self-heterodyne technique using an all-fiber unbalanced Mach–Zehnder interferometer with a 1.3 km delay fiber ($5.76\mu s$) and 20 MHz frequency shifter. One can see that the maximal PSD levels -25 dBc/Hz at 10 kHz frequency offset from carrier and -60 dBc/Hz at 100 kHz frequency offset from carrier are recorded with the laser operating with the linewidth of ~13 kHz (R=0.9). PSD levels for the laser operating the linewidth of 2.9 kHz (R=0.1) are lower by ~ (15-25) dBc⁄Hz over the range. Note that the reported spectrum range has been selected well above the active feedback circuit bandwidth thus avoiding its influence on the results [59]. Fig. 5 presents the relative intensity noise (RIN) spectrum measured with a low noise 1 GHz preamplifier and Agilent N9320A radio-frequency analyzer. One can see that all recorded RIN curves are well below −120 dB⁄Hz and does not depends significant on the laser linewidth. A slight difference in the RIN values is observed at frequencies less than 100 MHz only. The reported noise laser characteristics are similar to those reported with single-frequency fiber lasers [29,33,58,59].

In conclusion, we have implemented an active feedback loop based on a low-cost USB-DAQ to the configuration of DFB laser self-injection-locked to an external all-fiber ring resonator extending the frequency deviation range available for self-stabilization. Good agreement is found between the experimentally observed features and the numerically simulated features of the laser dynamics reported earlier [30]. 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. Particularly, new ability to control and tune the laser linewidth is attractive for many laser applications, including high-resolution spectroscopy, phase coherent optical communications, microwave photonics, coherent optical spectrum analyzer, distributed fiber optics sensing, in particular, phase-OTDR acoustic sensing [60-69].

Acknowledgments

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