Brillouin fiber laser passively stabilized at pump resonance frequency

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Abstract. *We demonstrate a single longitudinal-mode Brillouin ring fiber laser passively stabilized at resonance frequency with 1.7-m section of an unpumped polarization maintaining erbium-doped fiber. Two coupled all-fiber Fabry-Perot interferometers comprising the cavity in combination with the dynamical population inversion gratings self-induced in the active fiber provides an adaptive pump-mode selection and Stokes wave generation at same time. The laser is shown to emit a single-frequency Stokes wave with a linewidth narrower than 100 Hz.*

Introduction

Stimulated Brillouin scattering (SBS) is well known universal way to organize narrow-band lasing in fiber configurations enabling a variety of the performance characteristics [1-7]. Among single longitudinal-mode SLM fiber lasers, single frequency Brillouin lasers are intended for applications in distributed fiber sensors, optical measurement and processing. A class of SLM Brillouin fiber laser configurations with so-called doubly-resonant cavities (DRC) [8-10] exhibit low threshold, high spectral purity and low intensity noise. The Stokes wave in such lasers is generated with a short fiber ring cavity that is simultaneously resonant for both pump and Stokes radiations. Recently, we have reported an original mechanism for passive stabilization of SLM DRC Brillouin fiber lasers [11].

In this paper we report another approach for passive stabilization of SLM DRC Brillouin laser that demonstrates even narrower laser linewidth than achieved previously. Dynamical population inversion gratings induced in the length of the unpumped Er-doped optical fiber is shown to provide perfect mode selection and laser mode adjustment to the cavity resonance frequency at the same time. This adaptive all-fiber method is applied in combination with two coupled ring interferometers used for preliminary pump-mode selection and Stokes wave generation. The laser is shown to emit a single-frequency Stokes wave with the linewidth narrower than 100 Hz that manifests significant progress in the field of passively stabilized Brillouin lasers.

Experimental results and discussion

The experimental laser configuration is shown in Fig.1. Optical gain is provided by a 4.5-m segment of erbium-doped single mode fiber pumped by 1480-nm laser diode through a 1480/1550 WDM coupler. To get single frequency generation at ν_P the cavity combines two Fabry-Perot ring interferometers (FOFPI). This coupled cavity has superior intermodal spacing allowing the laser to operate only modes common for both interferometers [12, 13]. Low fidelity FOFPI-2 comprising a short fiber length is used as frequency-selective element. High fidelity FOFPI-1 comprising relatively long fiber is used as frequency-selective element and Brillouin laser ring cavity at the same time. The FOFPI-1 consists of 95/5 couplers C1, C2, polarization controller PC1 and contains 20-m length of a standard telecom fiber SMF-28 used as an efficient media for Brillouin wave generation. The radiation at Stokes wave frequency $\nu_S = \nu_P - \Delta_{SBS}$, where Δ_{SBS} is Brillouin shift, is emitted through the port B, while the ports D is used to control pump wave radiation at frequency ν_P. A fiber polarizer installed inside the main laser cavity ensures single polarization mode of the pump radiation. A 1.7-m section of unpumped erbium-doped PM fiber with a peak absorption at 1530nm as low as 5.5dB/m and in combination with narrow-band fiber Bragg grating (FBG) interferometer operates as adaptive ultra narrow-band reflector. The FBG interferometer comprises two shifted by ~0.8 cm uniform FBGs inscribed in the PM single mode optical fiber. It has 95% main reflectivity peak at 1547.37 with a full-width at half-maximum (FWHM) of ~0.07 nm. During laser operation the optical waves traveling in the unpumped fiber section in opposite directions interfere into a standing wave that causes inscription of the population inversion gratings in the fiber providing highly-selective reflection of the inscribing light through two-wave mixing effect [14]. Once the laser gets the resonance the increasing reflection from the unpumped fiber reduces the common laser cavity losses supporting lasing at the locked resonance frequency ν_P. After that any slow detuning of the frequency ν_P, for example, due to temperature variation are followed by the matching shift of the grating reflectivity peak.

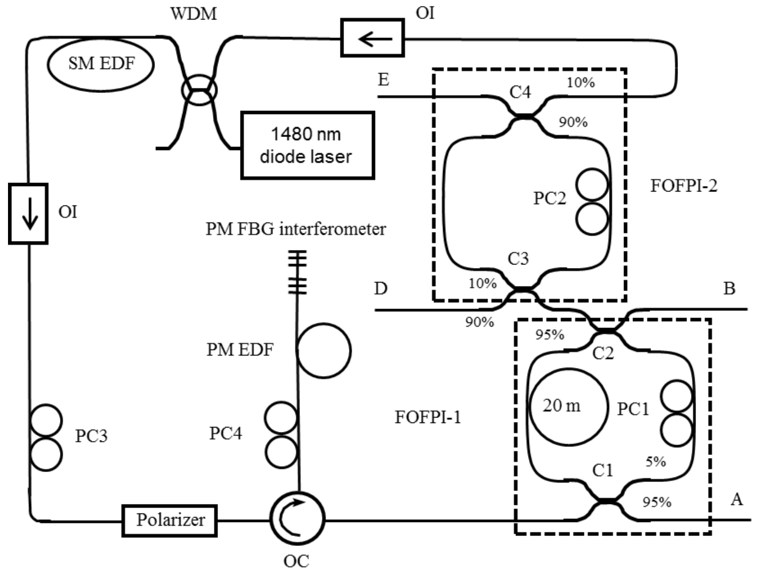

Fig. 1. The experimental laser configuration; OC- optical circulator, PC – polarization controller, C – coupler, OI – optical isolator, WDM - wavelength-division multiplexer, FOFPI – fiber-optic Fabry-Perot interferometer.

We have employed a delayed self-heterodyne technique to measure the linewidth of radiation emitted by the laser at pump and Stokes frequencies, i.e. from ports D and B, respectively. An all-fiber spliced Mach–Zehnder interferometer with a 25.3-km delay fiber in one arm and 15 MHz phase modulator supplied by polarization controller in the second arm is used for this purpose. The beat signal from the interferometer is detected by a 1 GHz photodiode and RF spectrum analyzer. Under assumption that the line shape is Lorentzian the delayed self-heterodyne spectrum width is simply twice measured laser linewidth. The frequency resolution of the used metrology is about ~100Hz.

Under pumping from 1480 nm laser, above the lasing threshold, the laser operates a single-frequency radiation at ν_P confined near the peak of the FBG interferometer reflectivity. At low diode powers no radiation at the Stokes frequency ν_S is recorded from the port B. The full laser linewidth at half-maximum (FWHM) is estimated to be 300 Hz. Intentional light losses introduced in any of FOFPI-1 or FOFPI-2 arms immediately suppress lasing thus demonstrating that the laser operates at a frequency mode common for both FOFPIs.

With increase of diode power the Stokes radiation could be recorded at port B. Since the pump frequency ν_P is resonant for both FOFPI-1 and FOFPI-2 the power circulating inside FOFPI-1 with factor ~35 higher than power at the interferometer input. This supports effective generation of the Brillouin radiation in FOFPI-1 comprising longer peace of fiber and possessing higher fidelity rather than FOFPI-2. The pump-to-Stokes power conversion efficiency is higher when FOFPI-1 is resonant not only for the pump, but also for the Stokes wave frequency ν_S. To make the cavity resonant for pump and Stokes waves simultaneously we used to cut 20-m length fiber piece-to-piece keeping control of the Brillouin threshold power after each cut. Under perfect resonance conditions the Brillouin threshold power recorded from the port D is minimal and is about 4 mW.

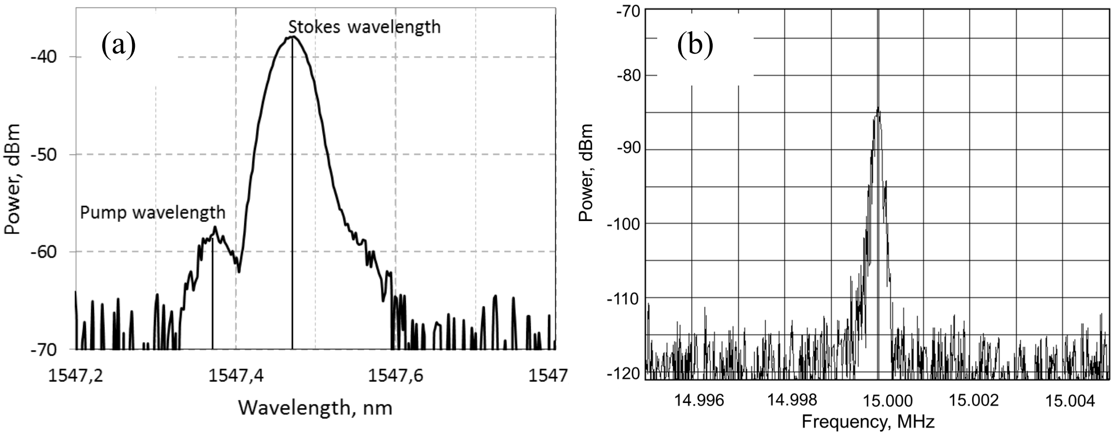

Fig. 2. Brillouin laser optical spectra in port B with 5 mW pump (a)
and delayed self-heterodyne spectra of the Stokes radiation (b)

Fig. 2(a) shows Brillouin laser optical spectra recorded through the port B at 5mW level of the pump power emitted through the port D. One can see a pronounced peak at ν_S that is ~20dB higher than the peak associated with Rayleigh scattering of the pump wave at ν_P. The output Stokes power is about 0.3 mW that corresponds to ~30% of the pump-to-Stokes power conversion efficiency. Due to high spectral contrast this signal could be further amplified up to tens mW level by an additional Er-doped amplifier without significant degradation of the signal/noise ratio. The measured Stokes wave linewidth is expected to be much narrower than the linewidth of the pump wave.

Fig. 2(b) shows the delayed self-heterodyne spectrum of the Stokes wave that highlights the record Stokes line FWHM to be less than 100 Hz that is behind the resolution limit of the used metrology. In time domain, pump and Stokes power exhibits stable CW behavior during long time intervals (0.2 – 1 s), which are interrupted by short-time jumping typical for mode-hopping. The origin of mode-hoping could be attributed, in particular, to the effect of refractive index changes in rare-earth doped fibers that is also stimulated by the population inversion gratings [15,16].

Conclusion

We have demonstrated SLM Brillouin fiber laser with a short ring cavity that is simultaneously resonant for both pump and Stokes radiations. The pump fiber laser was passively stabilized at resonance frequency, employing mechanism of population inversion gratings induced in the length of the unpumped Er-doped optical fiber. The laser is shown to emit a single-frequency Stokes wave with the linewidth narrower than 100 Hz.

Acknowledgements

This work was supported by the European FP7 IRSES project, the European Regional Development Fund and the Walloon Region (Mediatic project), the Interuniversity Attraction Pole program IAP PVII-35 of the Belgian Science Policy, program "Scientific and Research-Educational Cadres for Innovation Russia" of Ministry of Education and Science of the Russian Federation and project N 166039 CONACYT, Mexico.

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