Doubly-resonant Brillouin fiber cavity: algorithm for cavity length adjustment

C. A. López-Mercado[1], V.V. Spirin[1,2,*], E.A. Zlobina[3], S. I. Kablukov[3], P. Mégret[2], and A. A. Fotiadi[2,4,5]

[1] Scientific Research and Advanced Studies Center of Ensenada (CICESE), Carretera Ensenada-Tijuana No. 3918, Zona Playitas, 22860 Ensenada, B.C., México
[2] University of Mons, Faculte Politechnique, 31 Boulevard Dolez, B-7000 Mons, Belgium
[3] Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, acad. Koptyug ave. 1, Novosibirsk, 630090 Russia
[4] Ulyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk, 432970, Russia
[5] Ioffe Physical-Technical Institute of the RAS, 26 Polytekhnicheskaya Street, St. Petersburg 194021, Russia

We demonstrate a simple algorithm for adjustment of double resonance in a ring fiber Brillouin cavity. The perfect Brillouin cavity is resonant for pump and Stokes waves, simultaneously. The demonstrated approach is equally useful for design of single-mode fiber lasers with ultra-narrow optical spectra, Q-switched Brillouin fiber lasers and Brillouin random lasers. In our experiment the ring cavity with the length of 8 m has been adjusted for double resonance by the proposed method.

Introduction

The Stimulated Brillouin Scattering (SBS) is one of the most dominant nonlinear effects in optical fibers and fiber cavities. It is widely used for narrow-band lasing in fiber configurations, including random lasing [1].

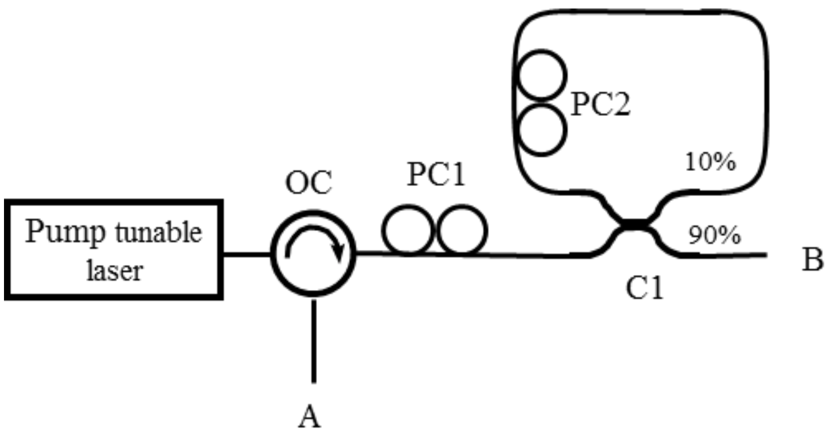

Fig.1. The experimental setup.

In particular, nonlinear ring SBS mirrors based on a single-mode fiber are the simplest, completely passive and rather universal way to organize gigantic pulse generation in a fiber laser operating at any wavelength. Various configurations of Brillouin lasers have been reported, offering a large variety in performance characteristics [1-7]. In spite of their extremely high efficiency for the pulse production (a typical peak/average power contrast is 10^5) the application of pulsed Brillouin lasers is limited due to their low pulse-to-pulse stability. The instabilities are caused, in particular, by random nature of

Rayleigh backscattering and lack of perfect resonances for Rayleigh scattered and Brillouin Stokes waves to the ring cavity. A perfect adjustment of the cavity for double resonance behavior could help to solve this problem.

On other hand, Brillouin fiber lasers with so called doubly-resonant cavity have been recently reported [8-11]. These lasers generates ultra-narrowband single-mode radiation and demonstrate low threshold, high spectral purity and low intensity noise. They are promising for a variety of applications, such as coherent optical communication, interferometric sensing, coherent radar detection, and microwave photonics. In these lasers the radiation is generated with a short ring cavity, which is simultaneously resonant for pump and Stokes waves.

In this paper, we proposed a simple method allowing adjustment of double resonance in the ring Brillouin fiber cavity of any length and for any operating wavelength.

Experimental setup and results

The experimental setup is shown in Fig. 1. The fiber ring cavity is pumped by a tunable laser Agilent 81940A with 100 kHz linewidth operating in wavelength sweeping mode. The pump power passed the optical circulator OC and the polarization controller PC1 is introduced into the ring cavity through 90/10 coupler C1. An all-fiber spliced ring cavity with the total length of $L \sim 8$ m is spliced from standard telecommunication SMF-28 fiber. The polarization controller PC2 is used to adjust the state of polarization inside the cavity. The transmitted and back reflected powers are detected with fast (~1 GHz) photodiodes, a digital oscilloscope and an optical spectrum analyzer.

The principle of operation is as the following. The length of the fiber ring cavity L defines a free spectral range (FSR) of the ring cavity:

$$FSR = \frac{c}{nL}, \qquad (1)$$

where c is speed of the light in the vacuum, and n is the refractive index of the SMF-28 fiber accounted here as $n \sim 1.468$ at 1550 nm [12].

When the pump laser frequency ν_L is in resonance with the Brillouin laser cavity, drastic increase of the pump power circulating inside the cavity in counter-clockwise direction occurs with maximum coupling of the power. The generation of the Brillouin Stokes wave is possible in clockwise direction at the frequency ν_S downshifted in respect to pump frequency ν_L by the Brillouin frequency shift $\Delta\nu_{SBS}$: $\nu_S = \nu_L - \Delta\nu_{SBS}$. Generation of the Stokes Brillouin wave is most efficient when it is also in resonance with the cavity mode. To get this resonance at ν_S the Brillouin shift $\Delta\nu_{SBS}$ should be equal to any integer number of FSR:

$$\Delta\nu_{SBS} = m \cdot FSR, \qquad (2)$$

where m is arbitrary integer. At this condition the Brillouin threshold in the cavity is minimal.

The Brillouin shift $\Delta\nu_{SBS}$ depends on the pump frequency ν_L and, hence, on the pump wavelength λ_L as:

$$\Delta\nu_{SBS} = 2\frac{nV_A}{c}\nu_L = 2\frac{nV_A}{\lambda_L}, \quad (3)$$

where $V_A = 5800\,m/s$ is the velocity of acoustic wave in the fiber [13]. Therefore, tuning of the pump wavelength λ_L is followed by tuning of the Brillouin shift $\Delta\nu_{SBS}$.

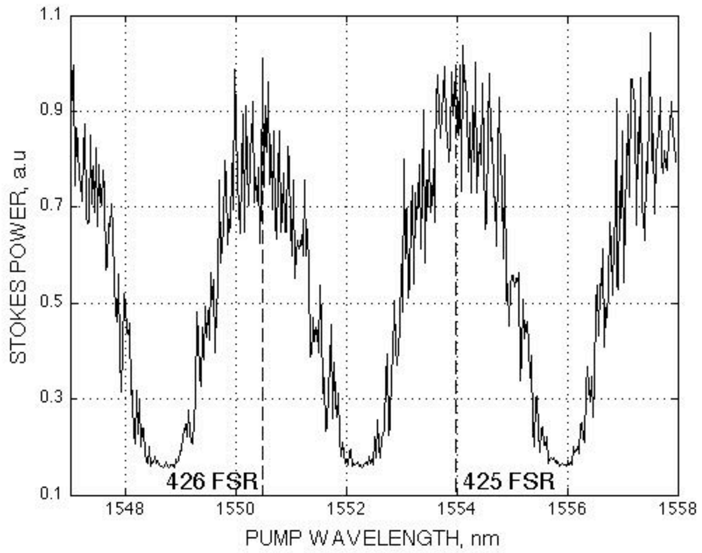

Fig.2. Stokes power at port A versus pump wavelength.

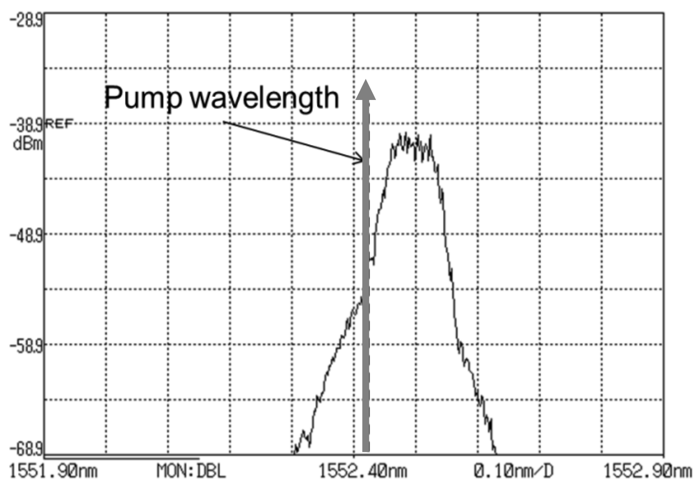

Fig.3 Optical spectra above Brillouin threshold at port A (a)

Fig. 2 shows the Stokes power recorded at port A of 8-m length cavity, when the pump laser wavelength is swept from 1547 to 1558 nm. Strong resonance peaks are observed at the pump wavelengths highlighting perfect resonance conditions for the Brillouin wave generated in the ring. From Eqs.1-3 we can indentify the integer number m. In particular, the first shown peak at $\lambda_{L1} = 1550.5nm$ corresponds to $\Delta\nu_{SBS} = 426FSR$, the second one at $\lambda_{L2} = 1554nm$ to $\Delta\nu_{SBS} = 425FSR$.

It is important that with these initial scanning data shown in Fig. 2 we can adjust the cavity to operate in double resonance at any selected wavelength λ_{L0}. Indeed, from the measured peak spacing $\lambda_{L2}-\lambda_{L1}$ (see, Fig. 2) we can recalculate through Eqs. 1-3 a number of discrete fiber lengths $\{\Delta L\}$ (relating to different orders m) that should be cut out from the fiber cavity to provide adjustment of the resonance. In particular, without changing the order we can define ΔL to decrease the resonance wavelength from λ_{L2} to λ_{L0} as:

$$\Delta L = \frac{c}{\Delta \nu_{SBS} n}\left(\frac{\lambda_{L2}}{\lambda_{L2}-\lambda_{L1}}-1\right)\left(1-\frac{\lambda_{L0}}{\lambda_{L2}}\right), \qquad (4)$$

For an example, one can check that adjustment of the original cavity resonant at $\lambda_{L2}=1554nm$ for resonance at $\lambda_{L0}=1552.4nm$, i.e. at the wavelength between the two resonances shown in Fig.2 requires reduction of the ring length by ~8.5 *mm*. Fig. 3 presents the optical spectra of Brillouin radiation at port A recorded at $\lambda_{L0}\sim 1552.4nm$ after such cavity adjustment. The resonance Brillouin threshold is ~5 mW.

Conclusion

Simple and efficient algorithm for getting doubly-resonant conditions in the Brillouin fiber cavity is demonstrated. Adapted fiber laser cavity is simultaneously resonant for the pump and Stokes radiations. In our experiment the ring cavity with the length of 8 m has been adjusted for double resonance by the proposed method.

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References
[1] A.A. Fotiadi, Nat. Phot. **4**, 204 (2010).
[2] A.A. Fotiadi, R. Kiyan, O. Deparis, P. Mégret, M. Blondel, Opt. Lett. **27**, 83 (2002).
[3] H. Ahmad, S. Shahi, and S.W. Harun, Laser Phys. **20**, 716 (2010).
[4] A.A. Fotiadi, P. Mégret, Opt. Lett. **31**, 1621 (2006).
[5] D. A. Grukh, A. S. Kurkov, I. M. Razdobreev and A. A. Fotiadi, Quant. Electr. **32**, 1017 (2002).
[6] C.E. Preda, A.A. Fotiadi, and P. Mégret, Opt. Express **20**, 5783 (2012).
[7] V.V. Spirin, J. Kellerman, P.L. Swart, and A.A. Fotiadi, Opt. Express **14**, 8328 (2006).
[8] S. Norcia, S. Tonda-Goldstein, D. Dolfi, J.-P. Huignard, and R. Frey, Opt. Lett. **28**, 1888 (2003).
[9] J.H. Geng, S. Staines, Z.L. Wang, J. Zong, M. Blake, and S.B. Jiang, IEEE Photon. Technol. Lett. **18**, 1813 (2006).
[10] S. Molin, G. Baili, M. Alouini, D. Dolfi, and J.-P. Huignard, Opt. Lett. **33**, 1681 (2008).
[11] V.V. Spirin, C.A. Lopez-Mercado, P. Mégret, and A.A. Fotiadi, Laser Phys. Lett. **9**, 377 (2012).
[12] Corning optical fiber, http://www.corning.com/opticalfiber/index.asp
[13] L. Thevenaz, Frontiers of Optoelectronics in China, vol. 3, num. 1, p. 13-21, 2010.