Evidence of Brillouin scattering in an ytterbium-doped double-clad fiber laser

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We have designed and performed an experiment that permitted direct observation of Brillouin backscattering in an Yb-doped double-clad fiber laser. Fifteen Brillouin-shifted frequencies were observed for the first time to our knowledge. We clearly demonstrate that stimulated Brillouin scattering is directly responsible for both fast transient dynamics of the laser and reduction of the laser's pulse width. © 2002 Optical Society of America

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High power double-clad (DC) fiber lasers have been of great interest for a few years. The DC technology allows a high-power broad stripe laser diode to be coupled in a fiber with good launching efficiency. The range of applications of these high-power compact sources includes optical pumping of optical amplifiers or Raman lasers, medicine, and spectroscopy.[1–3] Yb-doped DC fiber lasers are good candidates for these applications in the spectral range 1–1.1 μm. The large absorption cross section of Yb ions near 980 nm facilitates a pumping scheme with easily available low-cost laser diodes. The large fluorescence spectral range is well adapted for high-power tunable laser applications[4] or use in a mode-locked regime for generation of femtosecond pulses.[5,6] High power confined in the single-mode core of a DC fiber laser favors nonlinear phenomena such as stimulated Brillouin or Raman scattering and the optical Kerr effect. Although these nonlinear effects could be of interest for specific applications,[1,5–8] they can also lead to some unexpected instabilities in the laser signal. In particular, stimulated Brillouin scattering (SBS) is expected to be at the origin of instabilities in high-power fiber lasers[9] or deformation of pulses in fiber amplifiers.[10] However, we have seen no reported evidence of SBS in high-power double-clad fiber lasers.

In this Letter we report the direct observation of cascaded Brillouin waves (both Stokes and anti-Stokes components were obtained) in an Yb-doped double-clad fiber laser. We designed and achieved a specific cavity involving an intracore Bragg grating leading to a laser linewidth lower than the Brillouin shift. The spectral width of the grating was greater than the Brillouin shift, thus permitting the emergence of backscattered waves through the Brillouin effect. In addition, we demonstrate that SBS is responsible for fast transient dynamics on the output signal.

The experimental setup is shown in Fig. 1. The amplifying medium is a 30-dBm Yb-doped amplifier manufactured by Keopsys (Lannion, France). This system uses both DC technology to achieve high intracore power and a side-pumping technique that allows both fiber ends to be free. Light incident upon the embedded V groove undergoes total reflection in such a way that the reflected light propagates along the fiber axis. In our case this technique allows us to couple ~70% of the incident power into the inner cladding of a DC fiber. The doped fiber length is ~4 m, permitting the absorption of the total launched pump power (the pump absorption coefficient is ~3 dB/m). The core diameter is 7 μm, and the corresponding numerical aperture is ~0.12. The inner cladding is a 125 μm × 125 μm square, and its numerical aperture is 0.45. The pump laser diode operates at 975 nm and has a maximum available output power of 3.7 W. Single-mode fibers at $\lambda = 1$ μm are spliced to both ends of the DC fiber. One of these fibers contains an intracore Bragg grating, which reflects 99% of light over a bandwidth of ~1 nm near 1082.8 nm. The optical cavity is formed by the Bragg grating and the 4% Fresnel reflection that occurs at the other fiber end. That end is used as the output mirror of the laser. The total fiber length between the two mirrors of the cavity is 10.5 m. The output signal is analyzed through either a high-speed photodetector (bandwidth, 50 MHz) coupled to a 400 MHz-bandwidth oscilloscope

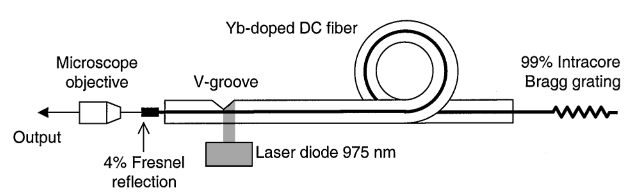

Fig. 1. Schematic of the experiment.

or an optical spectrum analyzer (maximum resolution, 0.01 nm).

The threshold of the Yb-doped fiber laser occurs for a pump power of 0.75 W. Below a critical value of the pump power $P_B = 1.25$ W (Brillouin threshold), the output intensity consists of an irregular train of pulses, as represented in Fig. 2(a). The pulse width is in the microsecond range, as shown in Fig. 3(a). The pulse exhibits fast oscillations owing to longitudinal mode beating at the free spectral range frequency of $\Delta\nu_{\mathrm{FSR}} = 9.5$ MHz. As the present authors and others discussed previously,[9] the origin of this unstable regime may be either the reabsorption of the laser photons in the unpumped part of the fiber or some quenching effect caused by the high concentration of Yb ions. Above the value of the pump power, $P_B = 1.25$ W, the dynamics is different, as represented in Fig. 2(b). The signal becomes more irregular and exhibits some intense pulses. Note that for this configuration we have limited the pump power to ~2 W to prevent irreversible damage that could occur with this kind of giant pulse. This value of pump power leads to an average output power of ~300 mW. Figure 3(b) presents details of one of these intense pulses just above the Brillouin threshold. The pulse exhibits a fast transient dynamics. The fast period is ~100 ns, which corresponds to the round-trip time of light in the cavity, i.e., $1/\Delta\nu_{\mathrm{FSR}}$. Figure 3(c) shows details of the intense pulse for a pump power of 1.5 W. We can see that one oscillation peak takes the most important part of the pulse energy. This phenomenon considerably reduces the pulse width (less than a few nanoseconds and below the resolution of our detection) and therefore increases the peak power. This kind of instability has already been reported in Yb-doped double-clad fiber lasers[7–9] and is usually attributed to SBS.[11]

Evidence of SBS is given in this Letter by the observation of the spectra of the laser below and above the threshold P_B of emergence of the instability. Below $P_B = 1.25$ W the spectrum exhibits a narrow line centered at 1082.8 nm [see Fig. 4(a)], which corresponds to the maximum of reflection of the Bragg grating. Its bandwidth is less than 0.01 nm, i.e., the resolution of our optical spectrum analyzer. For a pump power of 1.75 W, the spectrum clearly exhibits several orders of frequency-shifted components, as shown in Fig. 4(b). The shift between successive components is $\Delta\lambda = 0.06$ nm, which corresponds to $\Delta\nu = 15.4$ GHz. This value is in good agreement with the theoretical SBS shift of 16 GHz calculated from the relation[11]

$$\Delta\nu_B = 2n\nu_A/\lambda_p\,, \qquad (1)$$

where $n = 1.45$ is the refractive index, $\nu_A = 5.96$ km/s is the acoustic velocity, and $\lambda_p = 1082.8$ nm is the pump wavelength of SBS. Cascade SBS is then clearly demonstrated in this experiment. The inset of Fig. 4(b) represents the spectrum on a logarithmic scale and allows us to count more than 15 Stokes and anti-Stokes components. We have verified that the number of higher-order Stokes components decreases when the pump decreases and that it vanishes below P_B. Let us mention that the observation of many Stokes components is made more easily in our configuration because of the presence of the Bragg grating. Indeed, the spectral bandwidth of the Bragg grating is low enough to permit laser oscillation on a stable, narrow linewidth smaller than the Brillouin shift near P_B; however, the bandwidth is high enough to permit the

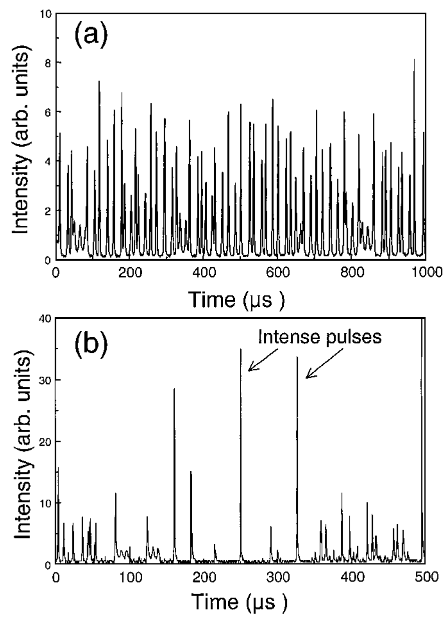

Fig. 2. Dynamics of the laser for pump powers of (a) 1 W and (b) 1.5 W.

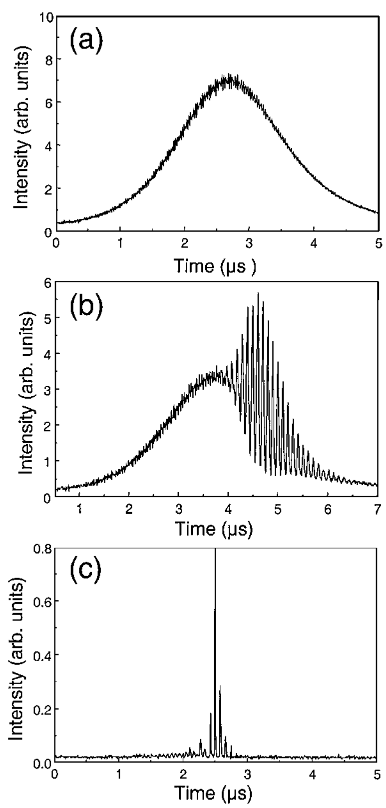

Fig. 3. Details of a pulse for pump powers (a) of 1 W, (b) just above P_B, and (c) of 1.5 W.

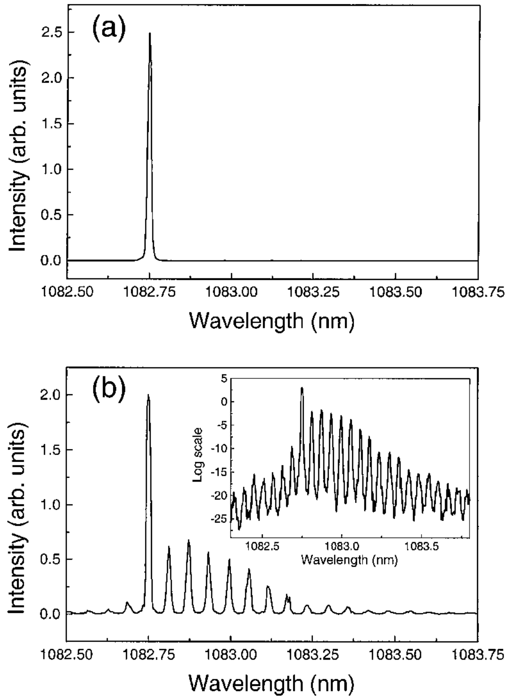

Fig. 4. Spectrum of the laser for pump powers of (a) 1 W and (b) 1.75 W.

oscillation of a great number of higher-order Stokes components. The bandwidth of the Bragg grating is then a good compromise to permit the observation of well-resolved Brillouin Stokes components. The complex dynamics of the laser, shown in Figs. 3(b) and 3(c), is then the consequence of strong competition among the various spectral lines that occur in this laser, benefiting from the same laser gain and coupled by means of the SBS nonlinear effect. The oscillation period of $1/\Delta\nu_{FSR}$ is characteristic of the transient dynamics of SBS.[11]

In this Letter we have clearly demonstrated that cascaded stimulated Brillouin scattering occurs in a self-pulsing high-power side-pumped ytterbium-doped double-clad fiber laser above the Brillouin threshold. More than 15 orders of Stokes and anti-Stokes waves have been observed. SBS leads to a reduction in the pulse width and to an increase in the peak power. In addition, we have pointed out the temporal instability that results from the emergence of Brillouin waves.

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References

1. V. I. Karpov, E. M. Dianov, V. M. Paramonov, O. I. Medvedkov, M. M. Bubnov, S. L. Semyonov, S. A. Vasiliev, V. N. Petropopov, O. N. Egorova, V. F. Hopin, A. N. Guryanov, M. P. Bachynski, and W. R. L. Clements, Opt. Lett. **24,** 887 (1999).
2. S. V. Chernikov, J. R. Taylor, N. S. Platonov, V. P. Gapontsev, P. J. Nacher, G. Tastevin, M. Leduc, and M. J. Barlow, Electron. Lett. **33,** 787 (1997).
3. L. Goldberg, J. P. Koplow, R. P. Moeller, and D. A. V. Kliner, Opt. Lett. **23,** 1037 (1998).
4. A. Hideur, T. Chartier, C. Ozkul, and F. Sanchez, Opt. Lett. **26,** 1054 (2001).
5. P. Adel, M. Auerbach, C. Fallnich, and H. Welling, in *Advanced Solid-State Lasers*, Vol. 50 of OSA Trends in Optics and Photonics (Optical Society of America, Washington, D.C., 2001), paper TuA 4.
6. A. Hideur, T. Chartier, M. Brunel, S. Louis, C. Ozkul, and F. Sanchez, Appl. Phys. Lett. **79,** 3389 (2001).
7. S. V. Chernikov, Y. Zhu, J. R. Taylor, and V. P. Gapontsev, Opt. Lett. **23,** 298 (1997).
8. Z. J. Chen, A. B. Grudinin, J. Porta, and J. Minelly, Opt. Lett. **23,** 454 (1998).
9. A. Hideur, T. Chartier, C. Ozkul, and F. Sanchez, Opt. Commun. **186,** 311 (2000).
10. K. Shimizu, T. Horiguchi, and Y. Koyamada, IEEE Photon. Technol. Lett. **4,** 564 (1992).
11. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, San Diego, Calif., 1989).