In-situ, spatially-resolved thermal and Brillouin diagnosis of a high-power ytterbium-doped fibre laser by Brillouin optical time domain analysis

Y. Jeong, C. Jauregui, D.J. Richardson, and J. Nilsson

We demonstrate an in-situ, spatially-resolved diagnosis of thermal and Brillouin characteristics of a double-clad ytterbium-doped fibre (YDF) laser operating at 1.09 μm. For this, we utilise a Brillouin optical time domain analysis technique based on 1.55-μm Brillouin pump and probe beams. We have measured and resolved a 2.4-K temperature difference across the YDF laser when it was running with 6.5 W of pump power. Based on the measured thermal and Brillouin characteristics of the YDF, we expect that its effective Brillouin gain coefficient would decrease by 20% for 1.09-μm radiation if an 80-K temperature variation is built up across it, as a result of the quantum-heating by the pump power.

Subject categories and indexing terms: *Lasers (Fibre lasers), Optics (Optical pumping)*

Introduction: The thermal characteristics of fibre gain media are closely linked to various aspects of their performance, e.g. efficiency, beam quality, spectroscopy, nonlinearity, material damage, etc. [1-4]. Therefore, it is of great importance to accurately diagnose them when the heat dissipation rate of the gain fibre is high e.g. because of high concentration, low efficiency, high pumping rate, or photo-darkening. Thus, there have been substantial research efforts to analyze these thermal characteristics in many respects [1-4]. Accurate thermal or thermally-related information of the active core, e.g. regarding any change of its properties, is particularly important because the core is the source of the quantum defect heating as well as the path for the signal [1].

In the first instance, some side detection techniques, e.g. thermal imaging or detection of upconversion fluorescence [4] appear to be the simplest options. However, in general they require cumbersome calibration processes to accurately retrieve the thermal information of an active core since the spectra and its strength can vary with the emissivity of the fibre and the ambient reflections, and the composition and condition of the active core. Furthermore, one serious drawback is that these techniques will not work if the fibre is packaged or covered by a non-transparent cartridge, normally used for protection, heat-sinking, etc.

Here we propose to use a Brillouin optical time domain analysis (BOTDA) technique [6] for the in-situ, spatially-resolved thermal diagnosis of high-power fibre laser systems and demonstrate it experimentally with an ytterbium-doped fibre (YDF) laser. We further utilise the measured characteristics to obtain the integrated Brillouin gain for the signal beam, which is broadened by the temperature variation along the fibre length induced by the quantum defect heating [5]. These Brillouin gain characteristics are particularly important for so-called single-frequency fibre sources [5]. Since the Brillouin gain is dynamically shifted by the longitudinal temperature variation created by the longitudinally-varying pump power, a spatially-resolved detection technique is required. We experimentally demonstrate that the BOTDA technique can both determine the temperature distribution and the Brillouin gain spectrum.

Experiments and results: The BOTDA technique was first proposed for the nondestructive measurement of single-mode optical fibre attenuation characteristics and has been a powerful, distributed sensing technique, particularly, for passive optical fibre systems [6]. Compared with the Brillouin optical time domain reflectometry (BOTDR), here a counter-propagating probe at the Stokes wavelength is used to stimulate the Brillouin scattering.

The BOTDA setup used for our experiments is depicted in Fig. 1. The output from a tuneable laser diode operating at ~1.55 μm is split into two arms, one for the pump and the other for the probe. The linewidth of the laser is below 1 MHz. The pump beam is modulated by an electro-optic modulator at 12.5 kHz into rectangular-shaped pulses of 30-ns duration and 3.75×10^{-4} duty cycle, which yields ~3-m spatial resolution. (The spatial resolution can further be improved by reducing the pulse duration to a minimum of ~10 ns.) The pulses are then amplified by an erbium/ytterbium-doped fibre amplifier (EYDFA) to ~900 mW of average power. On the other hand, the continuous-wave probe beam is frequency-downshifted by ~11 GHz with respect to the pump by an electro-optic modulator (EOM). The probe is also amplified by an erbium-doped fibre amplifier (EDFA), to ~2 mW. We stabilize the polarization states of the pump and probe beams by isolating the system from environmental disturbances and also by using in-line polarization controllers (PCs). Since the fibre laser that we are to characterize is based on an YDF which operates at ~1.09 μm, the use of ~1.55 μm beams for the BOTDA enables us to have a free optical channel to access and diagnose the YDF gain medium without disturbing it, even when it is strongly pumped.

The all-fiberized YDF laser consists of a ~10-m length double-clad single-mode YDF (CorActive Las-Yb-06-02), a fiberized pump/signal-combiner, a fibre Bragg grating (FBG) for feedback at 1.09 μm, and a multi-mode single-emitter pump diode at 915 nm. The YDF section is coiled and put into a metallic cartridge. The YDF has a core of 6.1 μm in diameter and a 0.13 numerical aperture (NA), which yields single-mode operation both at ~1.09 μm and ~1.55 μm. The pump absorption rate at 915 nm is ~0.8 dB/m. The measured slope efficiency with respect to pump power in the diode pigtail is 46%. The measured maximum output power is 2.8 W with 6.5 W of diode power.

The obtained BOTDA profiles of the YDF laser for different pump powers are shown in Fig. 2, where the section from z = 15 m to z = 25 m approximately represents the YDF section. A typical Brillouin-scattered spectrum obtained at z = 20 m is also illustrated in the inset. The bandwidth is ~62 MHz for ~1.55 μm. It is noteworthy that the gain bandwidth is already twice as broad as that of pure silica [7]. From the measured BOTDA data, we analyze the Brillouin frequency shift as a function of the fibre position and illustrate this in Fig. 3. We can see that the deviation of the Brillouin frequency shift from that measured at z = 25 m, i.e. Δf_B, varies with the fibre position. This corresponds to the local temperature change because no other condition, e.g. tension, was altered in our case [6]. As can be seen, Δf_B, i.e. the temperature variation, follows the trend of an exponential function. This is due to the fact that the local heat dissipation in the YDF is roughly proportional to the local absorbed power at the point that varies exponentially. We estimate that the overall temperature change across our YDF laser is $\Delta T = 2.4$ K at 6.5 W of diode power ($df_B/dT = 1.1$ MHz/K [7]).

This spatially resolved Brillouin gain can be integrated along the YDF to yield the overall Brillouin gain spectrum. The resulting, integrated, Brillouin gain spectrum is an important parameter for narrow-linewidth laser systems because the broader the spectrum, the lower the gain peak [5]. By extrapolating the measured parameters at ~1.55 μm to those at the YDF gain band, i.e. ~1.1 μm using the well-known wavelength-dependent characteristics of the Brillouin scattering [7], we can obtain that the thermal coefficient of the Brillouin frequency shift at ~1.1 μm becomes 1.6 MHz/K, and that the Brillouin gain bandwidth becomes 125 MHz. With these parameters we expect that if our fibre is further pumped to produce $\Delta T = 80$ K across the fibre length (which typically happens with multi-hundred watt high-power fibre laser systems [5].), the peak value of the broadened Brillouin gain spectrum at ~1.1 μm would further decrease by 20%, which seems a bit small in comparison with other fibres reported in [5], but note that the Brillouin gain bandwidth of the un-pumped fibre is already twice as broad as that of un-broadened pure silica [7].

Conclusion: We have demonstrated a BOTDA-based thermal and Brillouin diagnosis of an YDF laser system during its operation. The choice of diagnostic pump and probe beams at ~1.55 μm enables a spatially-resolved, non-destructive characterisation that does not interfere with the fibre laser operation. Our measurement was capable of resolving a 2.4-K overall temperature variation along the fibre core. Our results highlight that a wavelength multiplexed BOTDA technique can be a very useful real-time diagnostic tool for monitoring thermal and Brillouin characteristics or detecting hot spots in any type of fibre laser and amplifier systems.

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Fig. 1 Experimental setup.

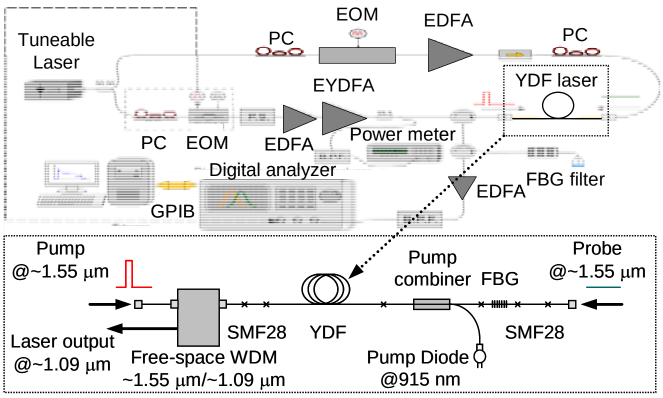

Fig. 2(a) BOTDA profile of the whole YDF laser system (un-pumped). Inset: Brillouin-gain spectrum at *z* = 20 m

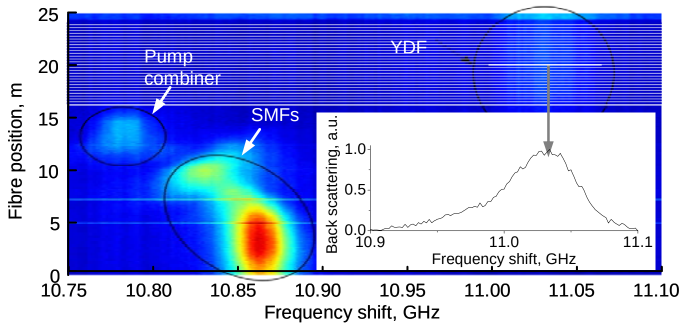

Fig. 2(b) BOTDA profiles of the YDF section for different pump powers.

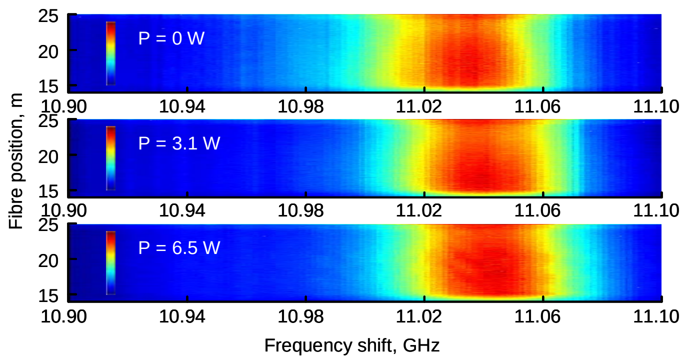

Fig. 3 Spatially resolved Brillouin frequency shifts for different pump powers. Solid lines represent exponential fittings or linear fitting, respectively.