Vector Brillouin optical time-domain analyzer for high-order acoustic modes

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Thanks to a double-frequency phase modulation scheme, we report a vector Brillouin optical time-domain analyzer (BOTDA). This BOTDA has a high immunity level to noise, and it features a phase spectrogram capability. It is well suited for complex situations involving several acoustic resonances, such as high-order longitudinal modes. It has notably been used to characterize a dispersion-shifted fiber, allowing us to report spectrograms with multiple acoustic resonances. A very high 57 dB dynamic range is also reported for 100-ns-long pulses simultaneously with a 16 cm numerical resolution. © 2010 Optical Society of America

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The Brillouin optical time-domain analyzer (BOTDA) is a fundamental tool for distributed measurements in optical fibers. It is a stimulated Brillouin scattering (SBS) pump–probe technique in which the counterpropagating probe is frequency scanned through the Brillouin–Stokes line [1]. The pump is pulsed, and thanks to a probe intensity time of flight, a distributed measurement of the Brillouin gain spectrum (BGS) is recovered. Because the probe detection operates in a low-frequency range from dc to a few hundred megahertz, the difficulty of this method is to discriminate the SBS signal from other perturbations, such as the pump Rayleigh backscattered light and a wide variety of low-frequency noise. Of course the Rayleigh component might be filtered out with a Bragg grating or an interferometer, but these devices are temperature and vibration sensitive and require a continuous monitoring. Besides, the light propagating in an optical fiber might induce a significant backward and forward intensity and phase noise in the ∼0–1 GHz range [2]. Because of its wide continuous spectral spread or nonperiodic distribution, this noise cannot simply be removed with an optical filter, especially if it is copropagating with the probe. On the other hand, higher-order longitudinal acoustic modes are of potential interest [3,4]. Contrary to the forward guided acoustic wave Brillouin scattering in the 0–1 GHz range [5], these backward modes are stimulated and could be observed with a BOTDA. Their frequency is close to the Stokes line, in the ∼9–12 GHz range for 1550 nm light. If their absolute frequency is quite high, as they beat with the other, they will also lead to low-frequency oscillations determined by their frequency spacing, typically a few hundred megahertz. These modes have been observed in photonic crystal fibers [6]. As they partially probe the cladding structure, their frequencies are dependent on the geometric parameters of the fiber [7]. In the near future, they could allow us to go beyond traditional temperature and longitudinal strain sensing. Applications such as distributed diameter deviation sensing or transverse strain sensing could be considered.

In this Letter, we report a vector BOTDA (VBOTDA) that is insensitive to low-frequency noise, which results in a high dynamic range (DR). Let us mention that vector SBS measurements have been performed in the continuous operating mode with a vector network analyzer [8]. In the context of distributed sensing, phase modulation has been implemented: the intensity pulse of the pump is replaced by a phase pulse for the purpose of spatial resolution enhancement [9]. With a Brillouin optical time-domain reflectometer, distributed measurements of the frequency shift of two peaks have been observed [10], but no spectrogram was reported. The VBOTDA principle is summarized in Fig. 1. The emission of a low-noise ∼500 kHz FWHM [11] distributed-feedback (DFB) laser diode is split to generate a pulsed pump and a continuously modulated probe. The VBOTDA is very similar to a standard BOTDA [12] except that the intensity modulator that usually modulates the DFB in order to synthesize the probe is replaced by a phase modulator (PM). Additionally, this PM is driven by two frequencies instead of a single one. Thanks to a double-frequency phase modulation scheme, we report a vector Brillouin optical time-domain analyzer (BOTDA). This BOTDA has a high immunity level to noise, and it features a phase spectrogram capability. It is well suited for complex situations involving several acoustic resonances, such as high-order longitudinal modes. It has notably been used to characterize a dispersion-shifted fiber, allowing us to report spectrograms with multiple acoustic resonances. A very high 57 dB dynamic range is also reported for 100-ns-long pulses simultaneously with a 16 cm numerical resolution. © 2010 Optical Society of America.

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![Fig. 1. Upper inset, double-frequency phase modulation principle (FLO, local oscillator frequency; FS, scanned frequency). Sidebands are created at ±FBS = ±(FS + FLO). When they enter the BGS resonance, they are either amplified or depleted. Lower inset, VBOTDA simplified representation (DFB, 1548 nm distributed-feedback laser diode; EO, intensity electro-optic modulator; EDFA1, ∼4 W peak output power; EDFA2, 1–10 mW cw; LNA, middle power low-noise amplifier stage 25 dB gain, ∼1 dB NF; Circ, circulator; OSC, oscilloscope; BPF, 120 GHz bandpass optical filter; PC, polarization controller).](image-url)
of a single one. The first of these frequencies, the local oscillator (LO) is fixed at $F_{LO} = 2$ GHz. The second frequency, $F_S$, is scanned to reconstruct the distributed BGS. The $F_S$ microwave power level is adjusted to minimize the carrier at $F = 0$. The LO power is set 10 dB below this level to be seen as a small perturbation. The probe spectrum is then compounded with sidebands at $\pm F_S, \pm (F_S - F_{LO})$, and $\pm F_{BGS} = \pm (F_S + F_{LO})$. The main interest of the phase modulation method is that no intensity modulation at $F_{LO}$ is generated after the PM. Indeed, there is, for instance, a beat note between the probe components at $F_S$ and $F_S + F_{LO}$, but this beat note is exactly counterbalanced by the beat note between the $F_S$ and $F_S - F_{LO}$ components, which have an opposite phase. However, if $F_S$ is tuned so that the sidebands $\pm F_{BGS}$ enter the BGS vicinity, the $-F_{BGS}$ sideband will be amplified while the $+F_{BGS}$ sideband will be depleted. The delicate phase modulation equilibrium is broken, which engenders an intensity beat note at the LO frequency. This signal can then be detected by the 5 GHz photodetector and the high-speed oscilloscope (>4 GHz bandwidth). Moreover, we have numerically checked that the contributions of the amplified and depleted sidebands both coherently contribute to the signal. The point is now to detect the amplitude of this $F_{LO}$ intensity modulation as a time function to obtain the BGS distribution for a given $F_{BGS}$. This procedure has many advantages. First, the useful signal is transferred to a high-frequency carrier (2 GHz), a spectrum area both free of the intense low-frequency perturbations and far from the Stokes lines. Second, in addition to the microwave power (proportional to the SBS optical intensity), the phase time of flight of this wave might also be estimated to construct a phase spectrogram. The demodulation procedure is as follows. The 2 GHz signal is divided by the oscilloscope is sliced into segments made of $N_{FFT}$ consecutive samples. Each segment has a 50% overlap with the previous one to optimize the resolution. After the application of a Blackman window, the power and the relative phase at $F_{LO}$ of each segment are calculated with a fast Fourier transform. To ensure a stable and reproducible initial phase reference, the LO generator, oscilloscope sampling clock, and pulse generator are all phase locked to the same 10 MHz clock reference. All the results presented in this Letter have been averaged 64 times.

A 300 m section of dispersion-shifted fiber (DSF) has been characterized. Because of its particular structure, the DSF displays several longitudinal acoustic resonances [2,10]. The experimentally observed intensity spectrogram is shown in Fig. 2. The pump pulse duration is 100 ns, i.e., a 10 m spatial resolution. With $N_{FFT} = 64$ and a 20 gigasamples/s oscilloscope sampling rate, the numerical resolution (NR) corresponds to 16 cm—a good compromise between the DR and the spectrogram rendering. In addition to the standard Stokes wave (labeled 1), three higher-order modes are visible. At around 100 m, a 50 m section of the fiber has been heated to 50 °C. A frequency step is clearly visible, which demonstrates that the VBOTDA is suitable for standard temperature sensing. For the main Stokes line, the temperature shift is $0.88 \pm 0.05$ MHz/°C—a standard value. The phase spectrogram is shown Fig. 3. It gives a different data insight. For instance, the highest resonance around 11.15 GHz is hardly visible on the intensity spectrogram, while it clearly appears in the phase spectrogram. The traces are also more regular. They are not subject to deep amplitude variations as is the case for the intensity ones. This stability could be exploited for precise maxima localization. Besides, phase spectrograms could also be employed for phase noise analysis or temporal reconstruction applications. Figure 4(a) displays a direct comparison of cross sections extracted from the two spectrograms at exactly the same spatial location. To show all the VBOTDA potential, Fig. 4(b) displays two similar cross sections obtained from the spectrograms of a standard single-mode fiber (SMF); the DR reaches 57 dB [13] (we have also measured 51 and 46 dB for 50 and 30 ns pulses, not shown Fig. 4).

With the SMF, we have performed acquisitions, down to NR = 2 cm $([N_{FFT} = 8])$. An impressive 52 dB DR is still observed. Checking that the VBOTDA behaves well with centimeter-level NR is a first step toward a high spatial resolution spectrometer, because the NR is an
ultimate limit for this apparatus. However, let us be reminded that presently, the VBOTDA resolution is still limited by the pulse duration or by the acoustic phonon lifetime. This is a well-known BOTDA limitation, and several strategies to overcome it have been successfully developed. They include the double-pulse [14], dark-pulse [15], differential pulse-width pair [16], and gain profile tracing [17] methods. As the VBOTDA transfers the BGS information to a high-frequency carrier, it is likely that most of these methods might be adapted to the VBOTDA. This would allow all the VBOTDA features with a centimeter level resolution, limited by the NR.

In summary, we have proposed and demonstrated a vector BOTDA scheme. No critical optical filtering is required. The only optical filter component that has been used is a broad stable 120 GHz bandpass filter to reject the erbium-doped fiber amplifier amplified spontaneous emission. Nevertheless, the VBOTDA is insensitive to low-frequency noise with up to 57 dB DR. This allowed us to report an intensity spectrogram with multiple longitudinal acoustic modes. A phase spectrogram has also been reported, for the first time to the best of our knowledge, in Brillouin reflectometry. Finally, the VBOTDA seems to be a promising tool notably for the study of high-order acoustic modes in photonic crystal fibers with potential applications in structural characterization.

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References and Notes
13. Because of PM to AM conversion, we estimate that for our parameters and an SMF with a 16 ps/nm/km dispersion, the 57 dB DR would probably be limited for fibers above 2 or 3 km. For a longer fiber, one should reduce FL0.