Complex Spectrum Analysis of Modulated Optical Signals Using Stimulated Brillouin Scattering

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***Abstract*—We introduce a novel method for the measurement of the spectral phase of modulated optical signals based on double-pump stimulated Brillouin scattering interaction and direct homodyne detection. This technique is combined with Brillouin high-resolution analysis to achieve a complete characterization of the complex optical spectrum. A 10-Gb/s nonreturn-to-zero signal with a 32-bit pattern modulated with an electroabsorption modulator is measured using this technique and its time-domain information (power and chirp) is obtained by inverse Fourier transform.**

***Index Terms*—Complex spectrum, stimulated Brillouin scattering (SBS), time-resolved chirp (TRC).**

I. Introduction

THE analysis of chirp effects and their interaction with chromatic dispersion, which is the limiting factor for optical links since the introduction of erbium-doped fiber amplifiers, has been a constant topic in source and modulator research in the last decades. After the identification of the chirp parameter α by Henry[1], many methods appeared for its measurement [2], [3]. More recently, the tendency has been to attempt the measurement of the instantaneous frequency deviations, the so-called time-resolved chirp (TRC), either directly, using frequency-to-amplitude conversion [4] or frequency-resolving techniques [5], or through the measurement of the phase in the spectral domain [6]. Some of these techniques are not limited to TRC measurements, but allow a complete characterization of the optical signal, both in amplitude and phase, enabling the measurement of signals with modulation formats based in amplitude, frequency, and phase modulation, or combinations of them, such as differential quadrature phase-shift keying. In this letter, we present a new method for the measurement of the phase of the optical spectrum of optical signals based on stimulated Brillouin scattering (SBS) which, in combination with a previously developed technique for the measurement of the amplitude spectrum [7], allows the characterization of the complex spectrum of a wide range of optical signals and the retrieval of their time-domain characteristics.

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II. Description of the Method

SBS is a quite complex nonlinear effect that has found many applications in sensing, optical processing, and slow light. However, to simplify our analysis, we will focus on its behavior as an optical narrowband filter [8]. When a spectrally narrow optical wave (pump) surpasses the Brillouin threshold, which is dependent of the nonlinear medium, the refractive index of the medium is modulated generating an acoustic wave, which causes part of the pump power to be backscattered with a frequency shift given by the Stokes shift [9]. If another optical wave, which we will consider the signal under test (SUT), is traveling in the opposite direction to the pump, and is in the interaction bandwidth of the SBS, it will be amplified proportionally to the power in this interaction bandwidth.

Every signal with a repetitive pattern has a spectrum that is composed by a train of scaled spectral lines separated by the repetition pattern frequency. If we consider a nonreturn-to-zero (NRZ) modulation format at a constant rate of B bit/s, the simplest case would be that of a "01" pattern, which constitutes a square signal of period $T = 1/\Delta\nu = 2/B$ and has a spectrum composed by the carrier plus sidebands at $\pm\Delta\nu$, $\pm 2\Delta\nu$, etc. If we use longer patterns, the effect will be the same using $\Delta\nu = B/L$, where L is the pattern length. The electrical field of an optical wave modulated with a repetitive pattern ES can be expressed from its development in Fourier series

$$E_S(t) = \sum_{k=-\infty}^{\infty} E_k(t) = \sum_{k=-\infty}^{\infty} A_k \exp j\left[2\pi(\nu_0 + k\Delta\nu)t + \varphi_k\right] \tag{1}$$

where E_k is the field of the kth component, with amplitude A_k and phase φ_k.

To measure the phase shift between adjacent spectral components of the optical signals, we select them by pumping SBS at those two frequencies simultaneously. When two spectral components of the SUT are at the Stokes-shifted wavelength compared with the double pump, they are greatly amplified by the SBS. Compared to the selected components, the amplitude of the rest of the signal is negligible. We can consider the signal after the Brillouin interaction as

$$\begin{aligned} E_{k,k+1}(t) &= G_B(A_k) \exp j\left[2\pi(\nu_0 + k\Delta\nu)t + \varphi_k + \varphi_B\right] \\ &+ G_B(A_{k+1}) \exp j\left[2\pi(\nu_0 + (k+1)\Delta\nu)t + \varphi_{k+1} + \varphi_B\right] \end{aligned} \tag{2}$$

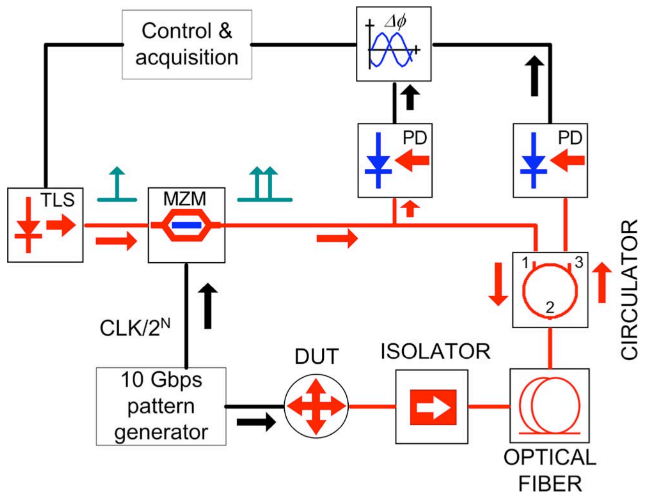

Fig. 1. Experimental setup for the measurement of the phase spectrum.

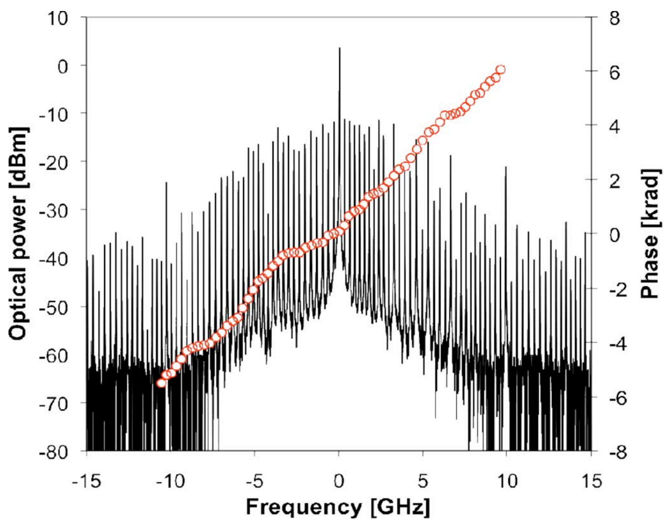

Fig. 2. Measured complex optical spectrum of a 32-bit pattern modulated at 10 Gb/s with an EAM. The solid line represents the optical power and the circles represent the accumulated phase for each spectral component. Phase reference is set to the carrier wavelength.

where G_B is the Brillouin gain, dependent on the optical power of the amplified spectral component and φ_B is the phase shift introduced by SBS, which is constant for the maximum gain frequency [10], thus not modifying the phase difference between these adjacent components.

If we detect the filtered signal with a photodetector, the beating between these components generates an electrical signal with a frequency given by the separation of the selected components and a phase equal to the difference between them

$$I_{k,k+1}(t) \propto \cos(2\pi\Delta\nu \cdot t + \Delta\varphi_{k,k+1}) \tag{3}$$

where $I_k, k+1$ is the detected current when components k and $k+1$ are selected, and $\Delta\varphi_{k,k+1} = \varphi_{k+1} - \varphi_k$. We can then extract the phase difference by comparison with a local oscillator of the same frequency. To obtain the absolute phase values, the phase differences must be accumulated. For convenience we set the phase of the optical carrier to 0°.

The narrow bandwidth of SBS (10–30 MHz depending on pump power [8]) is useful to achieve a very good resolution of the measurement, but it also imposes the requirement of the pump separation to be exactly the same as the component separation of the signal to avoid dependences with the pump scanning speed fluctuations. To achieve this, we generate the double pump by modulating a tunable laser source (TLS) with a Mach–Zehnder modulator (MZM) at the maximum extinction bias driven by an electrical signal obtained dividing the SUT clock by twice the pattern length ($\Delta\nu/2$). The modulation power is selected to achieve sufficient extinction of the carrier and higher order sidebands simultaneously. This way, neither the residual carrier nor the higher order sidebands reach the Brillouin threshold, and only the first modulation sidebands will pump SBS, generating the equivalent tunable dual frequency filter. The experimental setup is depicted schematically in Fig. 1.

A pattern generator is used to modulate the device under test with a 2^N bit NRZ signal. The clock frequency divided by 2^{N+1} is used to drive the MZM, obtaining the double-pump with frequency separation $\Delta\nu$, which is split to obtain the local reference after detection with a photodiode. Pump and SUT interact in an optical fiber, and the resulting signal is homodyned in a photodiode, comparing its phase with an electrical reference obtained from direct detection of the modulated TLS using an electrical phase detector. Results are recorded with an acquisition card. The measurement of the power of each spectral component is carried out using a BOSA-C from Aragon Photonics. Power and phase of each spectral component are measured, obtaining an array of complex values. Using inverse Fourier transform, the time-domain power and phase are obtained.

III. Experimental Results and Discussion

For this work, an electroabsorption modulator (EAM) driven with a $2^5 = 32$ bit pattern modulated at 10 Gb/s has been measured. This results in a frequency separation of 312.5 MHz among spectral components, following (1), which we consider as a good compromise between the spectral resolution and the number of points required for reconstruction of the time-domain signal. Its complex optical spectrum, with phase spectrum measured with our setup and power spectrum measured with a BOSA-C, is depicted in Fig. 2. The SUT spectrum is scanned with a 100-kHz linewidth TLS continuously swept over the measurement span. For the phase measurement, the TLS is modulated with the MZM driven by the divided clock signal, bandpass-filtered to obtain a 312.5-MHz sine wave. When the modulated TLS falls in the interaction SBS bandwidth with two spectral components of the SUT, a clear sine wave of 312.5 MHz containing the phase difference of those components can be observed at the output of the photodetector. After comparison with the reference, the phase difference is converted into a voltage by an electronic phase detector.

The TLS is a key component for the measurement to exhibit a good performance, as it directly determines the wavelength precision. To minimize these effects, the same TLS was used for

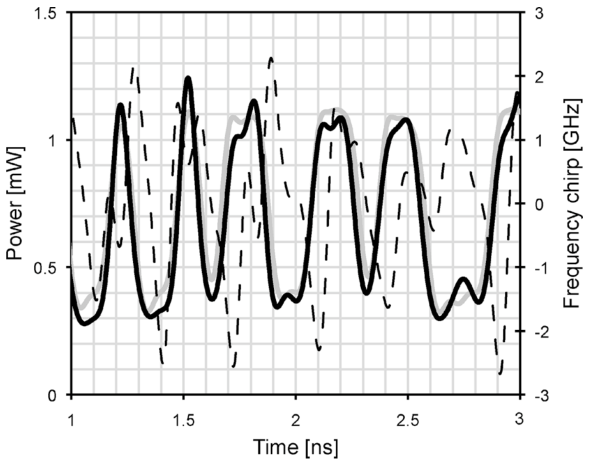

Fig. 3. Recovered instantaneous power (solid black) and frequency deviation (slashed black) from the inverse Fourier transform of the measured complex spectrum. A measurement of the modulation power by an oscilloscope (gray) is provided for comparison.

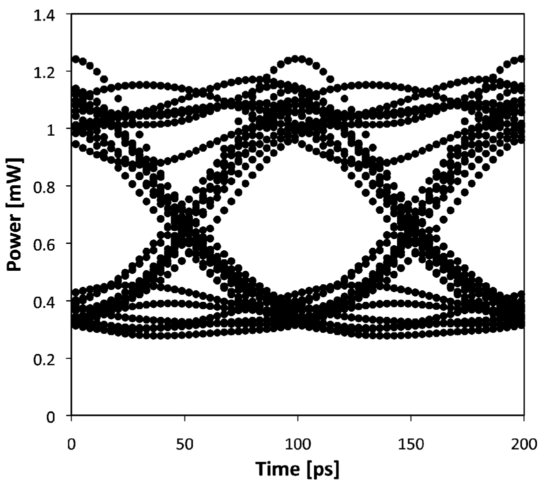

Fig. 4. Eye diagram of the recovered signal, result of the overlap of the 32 periods of the pattern.

both phase and power measurements simultaneously, allowing a perfect matching of the measured values. An additional averaging of subsequent TLS sweeps was performed using autocorrelation locking to minimize effects derived from the limited repeatability of the TLS and obtain more precise values for both phase and amplitude.

After precise optimization and calibration of the amplitude and phase response of the SBS interaction with our setup, we achieve a resolution of 10 MHz for the measurement of the amplitude spectrum and 20 MHz for that of the phase. Polarization of the SUT is aligned to obtain maximum SBS response, achieving a dynamic range that exceeds 80 dB for the amplitude and is about 60 dB for the spectral phase. Sensitivity in the measurement of the amplitude of the spectral components was −70 dBm, mainly limited by the spontaneous noise; and −60 dBm for the phase measurement, slightly lower due to the contribution of the residua of the signal beating in the photodetector.

The instantaneous amplitude, phase, and chirp are depicted in Fig. 3, where the 32-bit recovered pattern can be observed. The recomposed eye diagram of the signal is shown in Fig. 4. It is important to notice that the measurement uncertainties, which can be modeled as spectral noise, turn into distortion of the retrieved pattern, which is noise-free in time.

Compared with using frequency-to-amplitude conversion [4] for the measurement of the TRC, our technique is much more flexible and better suited for signals with high bandwidth, due to its independency with the modulation frequency thanks to the analysis at the pattern repetition rate, which is easily adjustable to obtain a convenient spectral separation. For low frequency, however, it is difficult to reproduce the level of detail possible with these techniques. In the field of the complex spectrum measurement technologies [6], [11], our technique has the best reported resolution and dynamic range for both the power and the phase spectra. The uncertainty of the measurement of each spectral component was estimated to be 1 dB in power and 5° in phase.

IV. Conclusion

We have presented a novel technique to measure the phase spectrum of optical signals based on double-pumped SBS. In combination with a measurement of the amplitude spectrum also with SBS, we have measured the complex spectrum of a 10-Gb/s optical signal and, through inverse Fourier transform we have reconstructed the instantaneous power, phase, TRC, and eye diagram. We believe this technique has a great potential for the measurement of ultrashort pulses, chirp of modulators, and modulation formats involving phase or frequency modulation.

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