Spectrally Slicing Coherent Optical Spectrum Analyzer for Measuring Complex Field Waveforms of Optical QAM Signals

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Abstract: We propose spectrally slicing scheme without any bandwidth limitation for measuring complex field waveforms of optical QAM signals. With our scheme, complex filed waveforms of 12.5-Gbaud 16QAM signals are measured even with 300-MHz bandwidth.

1. Introduction

Recently, quadrature amplitude modulation (QAM) [1,2] with optical coherent reception [3] has been introduced into the real use. For the signal monitoring in the coherent systems, we need to measure the complex field waveforms or constellation diagrams, and usually introduce optical coherent receivers including digital signal processing (DSP) with enough bandwidth [4]. After the signal equalization, signal distortion due to imperfection of optical devices and electronics cannot be correctly monitored. Without signal equalization, the simple and low-cost complex filed (amplitude and phase) measurement technique has been strongly desired. Although there have been reports on linear optical sampling techniques [5,6], the configuration is rather complex because of the need of ultrashort pulse sources.

We have proposed the simple and low-cost scheme for measuring the complex field waveform of QAM optical signals by using a narrow-band coherent receiver [7]. The optical spectrum of the measured signal is divided into multiple narrowband spectrally-sliced components, so-called slices, which are synthesized in the digital domain. It is called spectrally-slicing coherent optical spectrum analyzer (OSA). Although the signal spectrum cannot be correctly synthesized due to the phase and frequency fluctuations between spectral slices, the fluctuations are compensated for by DSP without any signal equalization. It is limited to measure just signal patterns in our scheme, but the long period such as pseudo-random bit sequence (PRBS) with bit length of $2^{15} - 1$ is possible to measure. We already reported the proof-of-concept experiment of the spectrally slicing measurement for QPSK signals [7]. In this paper, we investigate how much the spectrum can be divided. With the spectrally slicing coherent OSA with 300-MHz bandwidth, we measure the complex field waveforms of 12.5-Gbaud 16QAM signals.

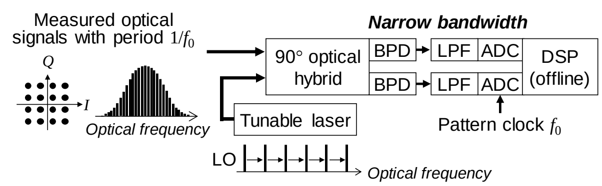

Fig. 1. Spectrally-slicing coherent optical spectrum analyzer.

2. Concept of operation

Figure 1 shows the configuration of the spectrally-slicing coherent OSA, which is the same as a conventional single-polarization coherent receiver with DSP. We assume that the repetition signal pattern is measured and it has the comb-like spectrum. Note that we can use the narrower-bandwidth photodetectors and digital electronics such as analog-to-digital convertors (ADCs). The ADC sampling and signal pattern are temporally synchronized. The concept of operation is shown in Fig. 2, in which the signal spectrum is divided into five narrowband spectrally sliced components, so-called slices. By tuning optical frequency of a local oscillator (LO) with even spacing Δf, the slices at the different frequency are subsequently measured with the narrow bandwidth. We determine the frequency spacing Δf so that the adjacent slices share the same part of spectrum, as shown in Fig. 2. The slices are stored through ADCs, and then they are synthesized into the original spectrum in the digital domain. Since the received slices are impaired with fluctuations of optical phase and frequency of the LO

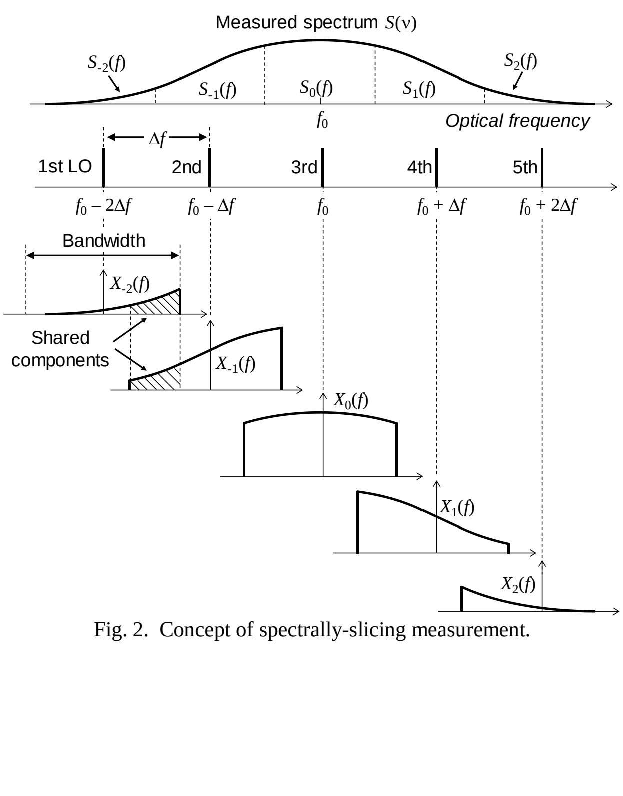

Fig. 2. Concept of spectrally-slicing measurement.

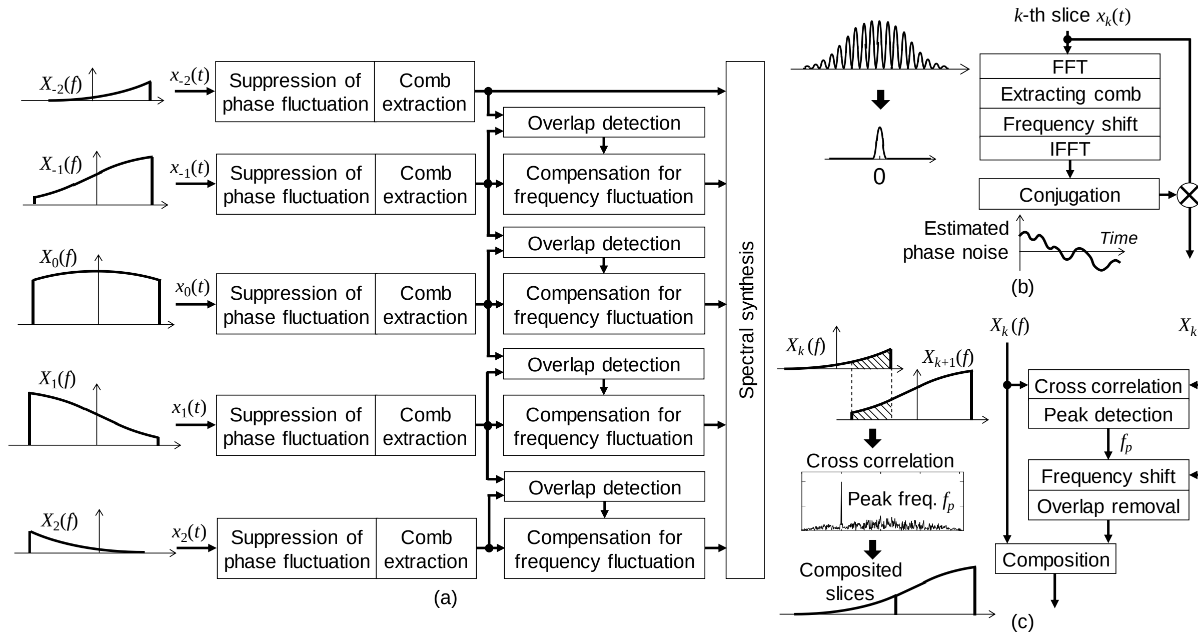

Fig. 3 DSPs for (a) the spectral synthesis, (b) suppression of phase fluctuation, and (c) compensation for frequency fluctuation.

laser, we cannot correctly recover the original spectrum. In order to compensate for the fluctuation, we introduce DSP as shown in Fig. 3(a). First, the phase fluctuation is suppressed, and then the comb peaks of the spectrum are extracted. After that, the frequency fluctuation is compensated for based on the shared components of the adjacent slices, and then we eventually synthesize slices into the original spectrum. Figure 3(b) shows DSP for suppressing the phase fluctuation. The comb components are found in the spectrum of the repetition signal, and they are broadened due to the phase fluctuation. By extracting one broadened comb component, we can get information of the phase fluctuation. After FFT of the stored data, the samples around the comb peak are filtered out and frequency-shifted to baseband. After IFFT of the processed samples, the phase fluctuation can be estimated, and it can be extracted from the original samples. Figure 3(c) shows DSP to compensate for the frequency fluctuation. The adjacent slices share the same part of spectrum, which is called shared components. By detecting the shared components, the frequency fluctuation can be detected. We calculate the cross correlation between the adjacent slices, and find the peak at the frequency in which the shared components are overlapped. One of the adjacent slices is frequency-shifted by the peak frequency, and then the shared component is removed, enabling to composite correctly two adjacent slices.

By IFFT of the synthesized spectrum, we can finally recover the temporal complex field waveform of the signal. By tuning delay and the offset phase of the complex field waveform, the constellation diagram is obtained. Note that signal equalization is never performed in the DSP, enabling to measure directly the distortion on the complex field waveforms. In addition, our scheme can operate independently of signal format, and it is possible to measure even probabilistic-shaped high-order QAM signals.

3. Experiment and Results

We experimentally evaluated the relationship between the measurement error and the slicing number. Figure 4 shows the experimental setup for the spectral slicing measurement of QPSK/16QAM optical signals based on PRBS with the bit length of $2^{15} - 1$. We obtained single-polarization 12.5-Gbaud QPSK/16QAM optical signals by using an optical IQ modulator driven by Nyquist-shaped electrical QPSK/16QAM signals. The period of the signal was 2.6 µs (80 ps × ($2^{15} - 1$)). After optical signal-to-noise ratio was adjusted to be 30 dB, the optical signals were measured by the spectrally slicing coherent OSA. Although we used a high speed digital oscilloscope with the bandwidth of 8 GHz, the narrowband measurement and the low-speed sampling were emulated in the digital domain. The slicing number N is determined by the measurement bandwidth. For example, when the measurement bandwidth was 300 MHz, the spectrum slicing number was 41. The oscilloscope was triggered by the pattern clock. The DSP was offline performed.

First, we investigated dependence on the slicing number N. The constellation diagrams of the recovered QPSK signals are shown in Fig. 5(a) and (b) when $N = 6$ and 126, respectively. We found clear four symbols in the constellation. The variance values of real and imaginary parts in the recovered symbols are plotted by closed circles and open circles in Fig. 5(e), respectively. The symbol fluctuation is not increased as increasing the slicing number even to larger than 100. Figure 5(d) shows the constellation of the QPSK signal without the spectral slicing measurement by the broadband self-dyne detection in which the same lasers were used for the signal generation and LO. The symbol fluctuation in the broadband self-dyne detection is larger than those of the spectrally slicing measurement. This is due to the oscilloscope bandwidth (8 GHz), and the spectrally slicing measurement can avoid the bandwidth limitation. In addition, we measured the constellation of the QPSK signals when IQ imbalance was deliberately given in the IQ modulation. The measured result is shown in Fig. 5(c). The IQ imbalance can be directly observed because signal equalization is not performed.

Finally, we measured the complex filed waveforms of 12.5-Gbaud 16QAM optical signals. With the spectrally slicing coherent OSA, the spectrum was divided into 41 slices, and then the slices were synthesized in the digital domain. The synthesized spectrum is shown in Fig. 6(a). For comparison, the results measured by the broadband self-dyne detection without spectral slicing is shown in (b). They are almost identical. The real part of the recovered temporal waveform of the 16QAM signal is indicated by red line in Fig. 7(a). Blue lines are the original waveforms used in AWG. We find the measured waveform by the spectrally slicing measurement is good agreement with the original waveform. The recovered constellation is shown in Fig. 7(b). For comparison, the result measured by the broadband self-dyne detection is shown in (c). In the recovered constellation, we can see clear 16 symbols even in the presence of the small IQ imbalance. These results show that the spectrally slicing measurement enables us to measure correctly complex filed waveforms without the bandwidth limitation.

4. Summary

We showed spectrally slicing coherent OSA without bandwidth limitation for measuring complex field waveforms of QAM optical signals. Even when the optical spectrum is divided into 100 narrowband spectral slices, it can be correctly synthesized. We demonstrated the spectrally slicing measurement of 12.50Gbaud 16QAM optical signals even with 300-MHz measurement bandwidth.

References

[1] M. Terayama *et al.*, OFC2018, **Th1F.2**, 2018.
[2] S. L.I. Olsson *et al.*, *Opt. Express*, **26**(4), 4522, 2018.
[3] K. Kikuchi, *IEEE J. Lightwav. Technol.*, **34**(1), 157, 2016.
[4] F. N. Hauske *et al.*, *IEEE J. Lightwav. Technol.*, **27**(16), 3623, 2009.
[5] K. Okamoto and F. Ito, *IEEE J. Quantum Electron.*, **45**(6), 711, 2009.
[6] K. Kikuchi and S. Y. Set, OECC2013, **TuR2-1**, 2013.
[7] K. Igarashi and N. Urakawa, OECC2019, **ThC2-4**, 2019.

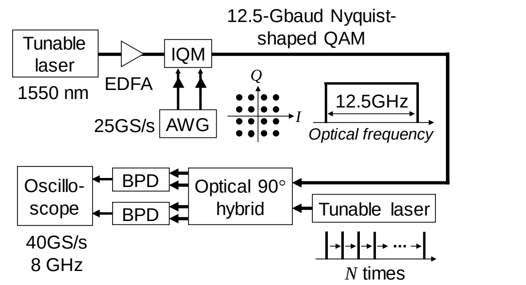

Fig. 4 Experimental setup for the spectrally slicing measurement.

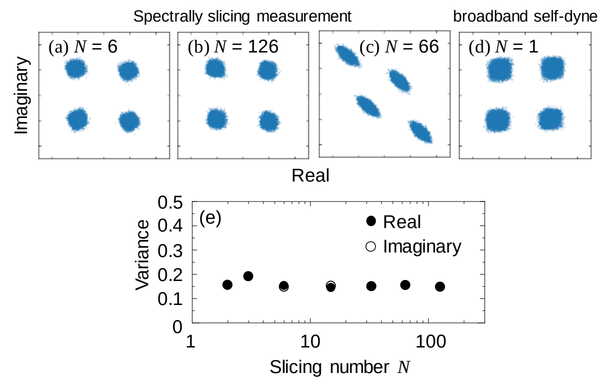

Fig. 5 Constellation diagrams measured by spectral slicing at (a) $N = 6$, (b) 126, and by (c) broadband self-dyne detection without spectral slicing. (d) Dependence of variance values of real and imaginary part of the symbol fluctuations on the slicing number N.

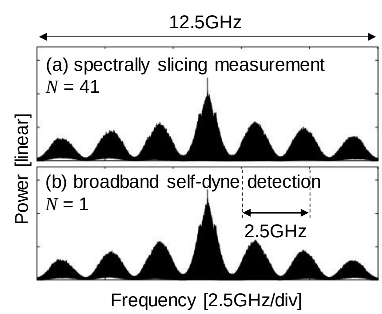

Fig. 6 (a) Synthesized spectrum of 16QAM signals at $N = 41$. (b) Measured spectrum in the case with broadband self-dyne detection without spectral slicing.

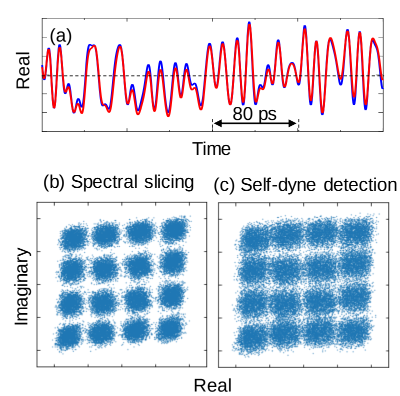

Fig. 7 (a) Real part and (b) constellation diagram of the recovered complex field waveform of 16QAM signals. (c) Constellation diagram measured by broadband self-dyne detection without spectral slicing.