Optical Complex Spectrum Analyzer (OCSA)

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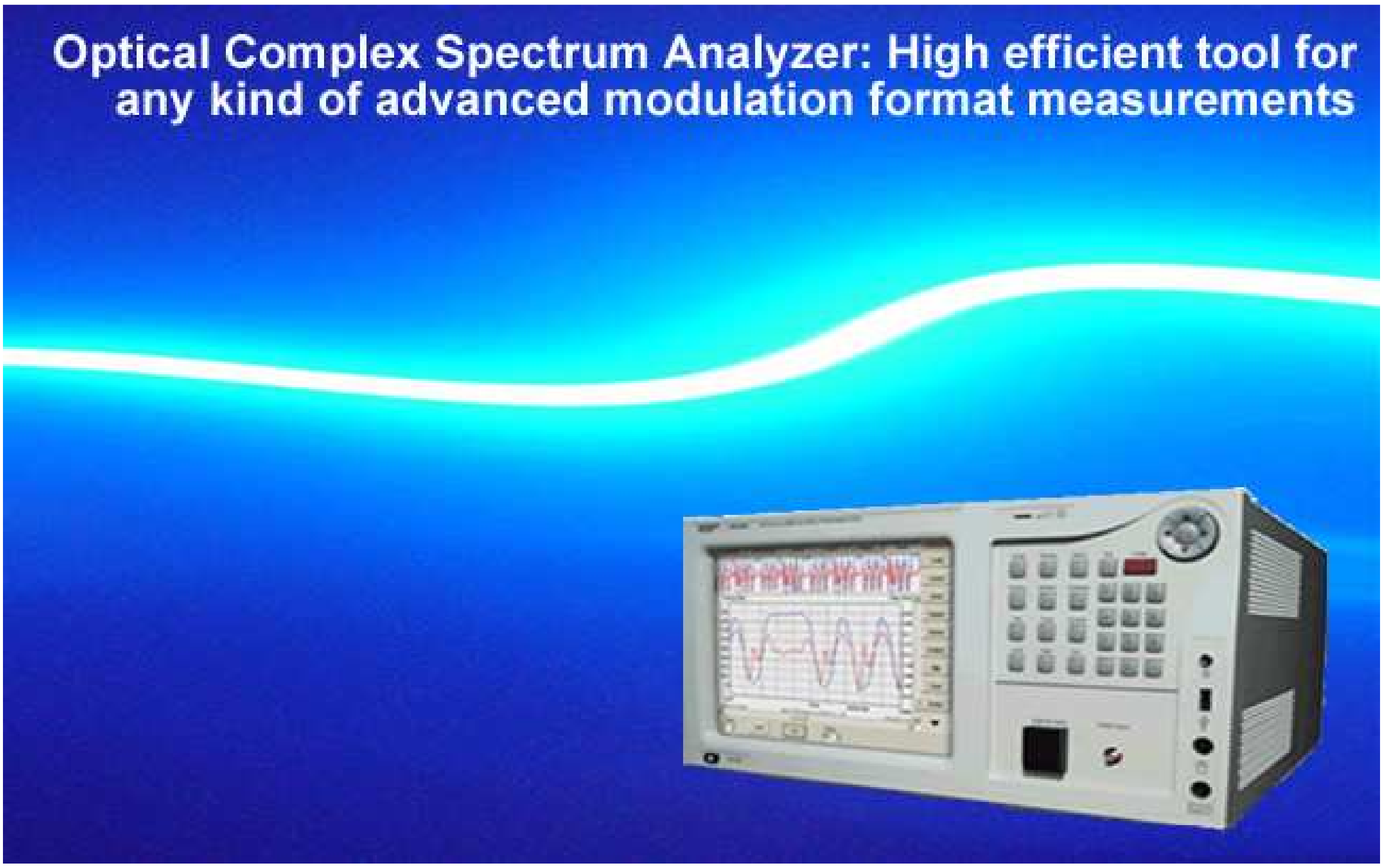
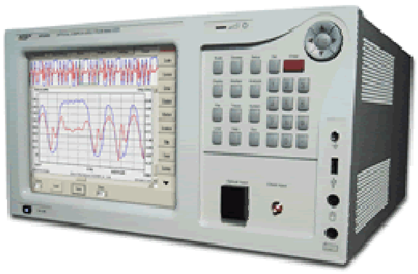


Optical Complex Spectrum Analyzer: High efficient tool for any kind of usual modulation format measurements

This application note proves the high efficiency of the Optical Complex Spectrum Analyzer AP2441B/AP2443B in measuring and testing any kind of usual modulation formats. Compared to a standard oscilloscope, the Optical Complex Spectrum Analyzer AP2441B/AP2443B has a maximum bandwidth > 6 THz due the complex spectral analysis principle giving access to the optical phase and intensity both in frequency and time domains. Therefore, the Optical Complex Spectrum Analyzer has no baud/bit rate limitations. Examples of RZ short pulses (2 ps pulse-width), pulse time resolved chirp, Differential Phase-Shift Keying (DPSK) modulation and Quadrature Phase-Shift Keying (QPSK) modulation measurements are presented.



Usual modulation formats

Actually, different transmission systems are deployed around the world, each with their advantages and disadvantages, using technologies and specific modulation formats. Depending on the modification method of the transmission parameters, several modulation formats and multiplexing schemes can be produced as depicted in figure 1. It lists the main modulation formats used actually in optical telecommunication systems.

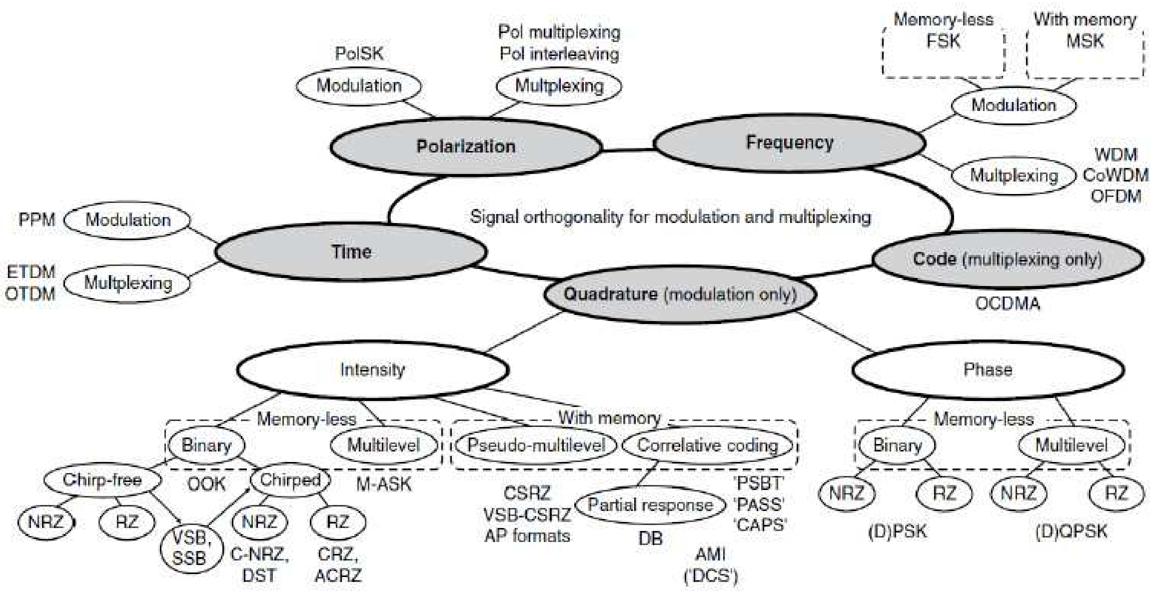


Figure 1: Classification of the most important modulation formats and multiplexing schemes used in optical communications systems

In the following paragraphs, we will detail some modulation formats commonly used in telecommunication systems. This is not an exhaustive list of existing modulation formats but a presentation of the interesting ones measured by our Optical Complex Spectrum Analyzer (OCSA) AP2441B/AP2443B.

▪ Amplitude modulation

✓ NRZ-OOK modulation : Non Return to Zero-On/Off Keying

This is the simplest way to generate an optical modulation. This binary modulation has two modulation states: typically in optical domain, the "1" and "0" states mean respectively the maximum and the minimum intensity of the optical signal. There are no intermediate states. This encoding is very simple to implement, just by using directly modulated lasers with two states electrical signal. The laser beam extinction and emission will correspond respectively to the low and high levels. However, this modulation format can lead to a misinterpretation if the states between the emission and the reception are reversed. In addition, the NRZ modulation does not have an intermediate state; it can be difficult to synchronize the emission and the transmission, and to achieve a clock recovery.

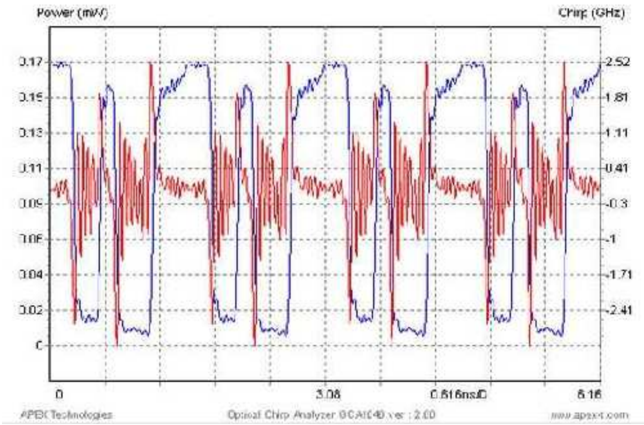


Figure 2: 10 Gb/s NRZ modulation Intensity (blue trace) and Chirp (red trace) measured by the Optical Complex Spectrum Analyzer

At 10Gbps with conventional NRZ-OOK modulation format, polarization mode dispersion (PMD) constitutes a problem for certain legacy fibre infrastructures. At 40Gbps still with NRZ-OOK, the PMD issue becomes more stringent, while at 100Gbps all operators (even those having deployed recent fibre infrastructures) will have to face PMD impairments. The figure 2 shows the intensity (blue curve) and the chirp (red curve) as function of the time measured by our OCSA AP2441B/AP2443B.

✓ RZ modulation : Return to Zero On/Off Keying

This modulation is very close to the NRZ-OOK modulation. Although it has two states, the signal can be in a low state between two successive bits, as depicted in figure 3 (succession of "1" or "0"). This modulation is self-timed (no need to transmit a clock signal in addition to the modulated signal in order to synchronize the transmitter and the receiver) and overcomes some disadvantages of NRZ signal. This modulation can be obtained electronically by directly generating an electric RZ signal or optically by adding a pulse chopper (an optical intensity modulator controlled by the clock frequency) to a NRZ optical signal generator. Therefore, this makes this modulation format a little more complex with respect to a NRZ modulation.

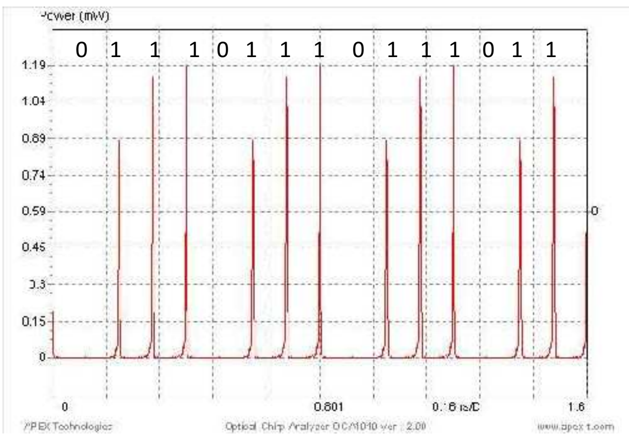


Figure 3: 10 Gb/s RZ modulation (2ps pulses) Intensity measured by the Optical Complex Spectrum Analyzer

Chronologically, equipment manufacturers have proposed to use RZ-OOK formats rather than NRZ-OOK, due to their better OSNR (Optical Signal to Noise Ratio) sensitivity and PMD tolerance (a short pulse being more robust to differential group delay than a large one).

✓ CSRZ modulation: Carrier Suppressed Return to Zero

It is a pseudo multi-level modulation format for which the signal intensity can be zero between two successive bits (as for RZ modulation) and the optical phase is set to 0 or π between two successive bits. Thus, following this alternative phase inversion, the optical field of the half of the bits has a positive sign, while the other half has a negative sign. Therefore, this leads to a null signal envelope that removes the central carrier optical frequency. Because of its significant robustness when facing intra-channel nonlinearities, CSRZ has been chosen by lot of experts for the first implementation of 40Gbps WDM transmission. The tolerance of CSRZ to intra-channel nonlinearities can be explained by the π phase alternation which affects its successive pulses. This π phase alternation permits to reduce the pulse spreading speed due to chromatic dispersion and thus the accumulation of intra-channel four-wave mixing (IFWM) and intra-channel cross-phase modulation (IXPM).

▪ Amplitude modulation

✓ DPSK modulation : Differential Phase Shift Keying

DPSK modulation format has been proposed in reason of its very good OSNR sensitivity, which is 3 dB better than that of NRZ-OOK. This OSNR sensitivity gain (due to the differential detection) enables for example to double the maximum reach of the WDM systems if non-linear effects don't affect the transmission. It can be intuitively understood by the fact that all the energy is dedicated to the data modulation, while in OOK half of the energy is contained in the carrier. Another interesting feature is the robustness to the Kerr nonlinearities, which can be schematically explained by the presence of energy in each bit slot which halves the peak power of the pulses with respect to NRZ-OOK. In DPSK, information is carried by the bits transitions and coded on two phase states {0, π} at the opposite of OOK modulation where data are carried by the bits themselves and coded on the carrier amplitude.

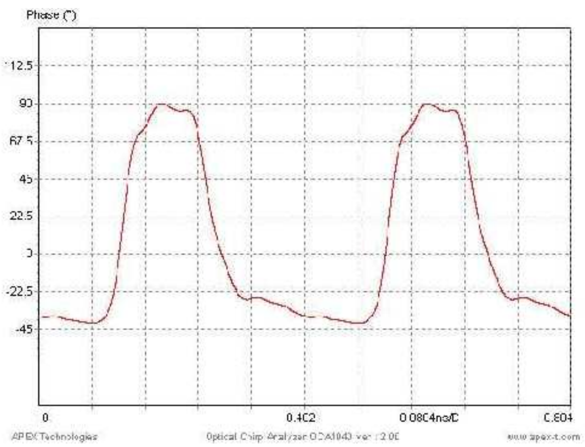


Figure 4: 10 Gb/s DPSK modulation Phase measured by the Optical Complex Spectrum, the two phase states are spaced by 135° and don't reach 180° due to the small RF power applied to the modulator.

✓ QPSK modulation : Quadrature Phase Shift Keying

In order to increase the number of bits per symbol and therefore the attainable speed for a PSK modulation, it is possible to encode information on a number of states greater than 2. For example, the QPSK format shown in figure 5, can encode data on four phase states with a 90° phase difference with respect to nearest neighbor. In consideration of the potential increase of the bit rate compared to a Binary-PSK (BPSK) signal, the QPSK signal will be more sensitive to noise and errors since the symbols of the constellation are closer than in a BPSK signal. Similarly for a BPSK signal which the information can be encoded differentially to produce a DPSK signal, a differential encoding can be done for a DQPSK signal. This last format has received the most attention in the optical communication field during the last 10 years

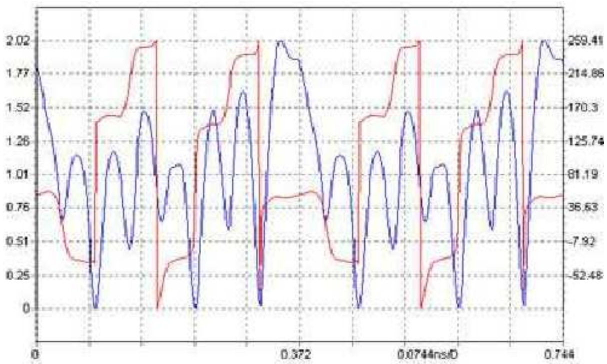


Figure 5: 40 Gb/s DQPSK modulation Intensity (blue trace) and phase (red trace) measured by the Optical Complex Spectrum Analyzer

▪ Combined amplitude and phase modulation

✓ Duobinary modulation

Duobinary format has also been proposed because Duobinary is particularly robust to accumulation of chromatic dispersion compared to NRZ-OOK. This feature is particularly valuable because it could permit to eliminate the need for tuneable dispersion compensation module (TDCM), which is mandatory when NRZ-OOK or CSRZ are implemented. Its spectrum bandwidth is also smaller than that of NRZ-OOK. In terms of OSNR sensitivity, Duobinary is 3-dB worse than NRZ-OOK, which limits its interest for ultra long-haul transmission applications.

Figure 6: 10 Gb/s Duobinary modulation Intensity (blue trace) and phase (red trace) measured with the Optical Complex Spectrum Analyzer

Duobinary has been proposed and adopted by all other equipment suppliers for their 40Gbps metropolitan transmission solution. The information is carried by the intensity of the carrier but a phase modulation (which does not carry any information) reduces the pulse spreading and the corresponding sensitivity to chromatic dispersion and intra-channel non-linear effects. In fact, after propagation, the conjunction of the frequency chirp and the chromatic dispersion leads to the transmission length limitation due the resulting Inter-Symbol Interference (ISI). Therefore, a π phase shift between two "1" bits separated by "0"bit which corresponds to the duobinary modulation, as shown in figure 6, can flexibly fight the chromatic dispersion effects. Indeed, the two bits "1" overlapped in the bit "0" due to the ISI are in phase opposition. Therefore, "1" bits are better separated producing an open eye and a low bit error rate (BER).

Optical Complex Spectrum Analyzer utility

Fast development of broadband communication services makes stringent the need for further capacity which creates new challenges for all the segments of the optical communication network. This large increase in the magnitude of the data exchanges is driving the research towards advanced modulation formats. Furthermore, this challenge is correlated with stringent requirements for high performance optical test equipments as an important tool to measure and adjust all kind of modulation formats. In this context, test equipment able to measure the optical phase as function of time remains a very important tool in the telecommunications industry, and in research laboratories.

Based on our core technology, APEX Technologies provides the world's first commercially available Optical Complex Spectrum Analyzer (OCSA) providing the capacity of optical phase measurement both in time and frequency domain for any modulation formats without any bit/baud rate limitations.

The patented method used by the Apex Technologies OCSA is based upon a spectral analysis of the optical field; it extracts the amplitude and the phase of each frequency component (whereas classic optical spectrum analyzers measure only the power spectral density, giving only the amplitude). By knowing the amplitude and the phase of each spectral component, the temporal variations of the amplitude and the phase can be calculated by means of the Fourier transform, providing the intensity, the chirp and the phase as function of time and display the eye diagram, the BER estimation and the EVM (Error Vector Magnitude). In the following paragraphs, we will present some application examples of the OCSA.

✓ Short optical pulse for RZ modulation

Most alternative measurement solutions are bandwidth limited because they measure RZ short pulses in the time domain, while the Apex Technologies OCSA series uses the complex spectrum to calculate the time domain results. The Apex Technologies method is only limited by the wavelength range of the optical complex spectrum analyzer. Actually, if the RZ modulated signal is inside the wavelength range of the optical complex spectrum analyzer it can be measured without distortion (figure 7). The maximum wavelength range offered by Apex Technologies is currently 110nm, covering both the C and L bands and giving a maximum temporal resolution of 75 fs. The optical complex spectrum analyzer is the perfect tool for RZ pulse analysis as well as for high bit rates NRZ signal (40 Gb/s, 160 Gb/s and up) measurements.

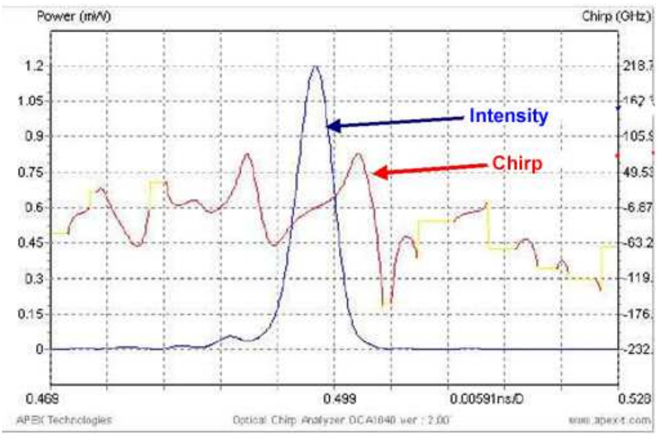


Figure 7: 10 Gb/s RZ modulation (2ps pulse width) measured by the Optical Complex Spectrum Analyzer

✓ Time resolve chirp

Most solutions used for time resolved chirp measurement are based on the frequency discrimination method. This method is based on the conversion of the frequency modulation (chirp) into intensity modulation using a Mach Zehnder interferometer (MZI). The intensity modulation is therefore analyzed with a standard oscilloscope. However, this method is not scalable experimentally to higher data rates (40 Gb/s and up) because of the bandwidth limitation of the MZI and the oscilloscope. With the optical complex spectrum analyzer, time resolved chirp is directly calculated from the optical complex spectrum, giving accurate results and excellent repeatability (figure 8).

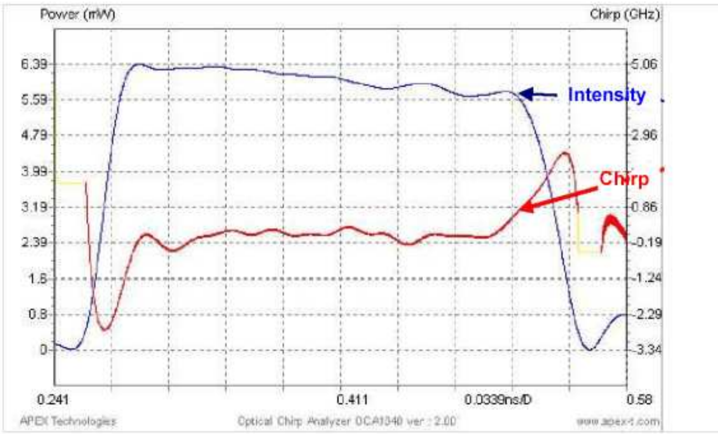


Figure 8: Intensity and chirp measurement of a z-cut LiNbO3 external modulator measured by the Optical Complex Spectrum Analyzer

✓ DPSK measurement

With DPSK modulation, a digital signal is represented by the phase of the optical carrier. DPSK modulation can be made either with a phase modulator or an intensity modulator (with the bias point adjusted at the minimum transmission).

Figure 9 depicts the intensity (blue trace) and the phase modulation (red trace) of a 10 Gb/s DPSK signals using an intensity modulator. In this case, the two phase states are exactly separated by 180°. These two phase states can be seen on the red trace.

Because of the intensity modulator, we can clearly see the drop in intensity during the phase transitions. For the phase modulation formats, the OCSA is able to display the optical constellation diagram (this is the fact that each modulation state is assigned by a point, the entire of these points represented in complex domain is called constellation)

With this constellation display (figure 10), we can see that the 180° phase change is well made but the bias adjustment was not correct (assymetry between the left and the right part of the graph).

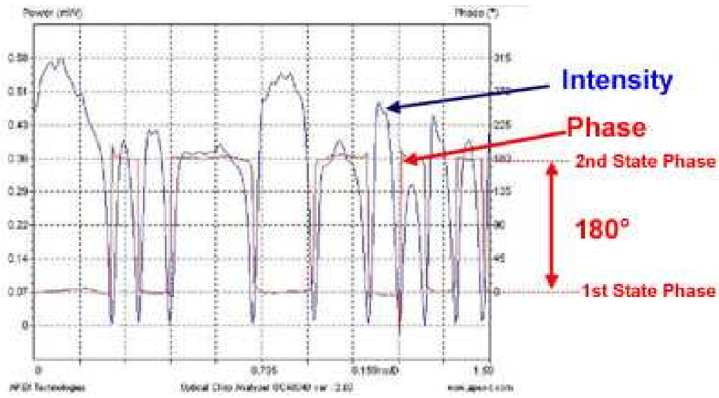


Figure 9: 10 Gb/s DPSK modulation realized with an intensity modulator and measured by the Optical Complex Spectrum Analyzer

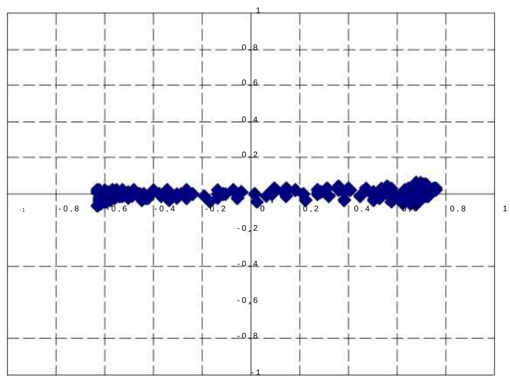


Figure 10: The constellation of a DPSK modulation displayed by the Optical Complex Spectrum Analyzer

DPSK modulation can be realized with a phase modulator also. In this case the intensity is stable over the time scale and only the phase is varying. When using a phase modulator, every kind of phase state can be obtained, so it is necessary to measure the time resolved phase to verify if the two phase states are spaced by 180°.

In this example (figure 11), RF power applied to the modulator was not strong enough and because of this instead of having two phase states spaced by 180° we now only

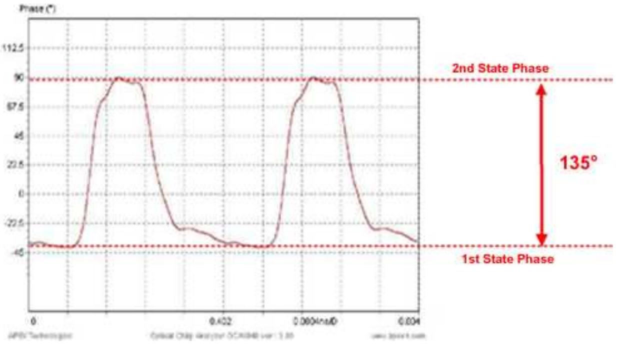


Figure 11: The phase of a DPSK modulation realized with a phase modulator and displayed by the Optical Complex Spectrum Analyzer

✓ QPSK measurement

Compared to DPSK modulation having only 2 different phase states, QPSK is coded with 4 different phase states. So, compared to a DPSK signal, QPSK is doubling the spectral efficiency (same spectral width but double bit rate).

Adjustment of a QPSK modulation is difficult to realize and there was a need of having an instrument to measure the phase variations as a function of time. Now with the OCSA, it is now possible to visualize this phase modulation and adjust all the modulation parameters accurately in order to improve the transmission quality (figure 12).

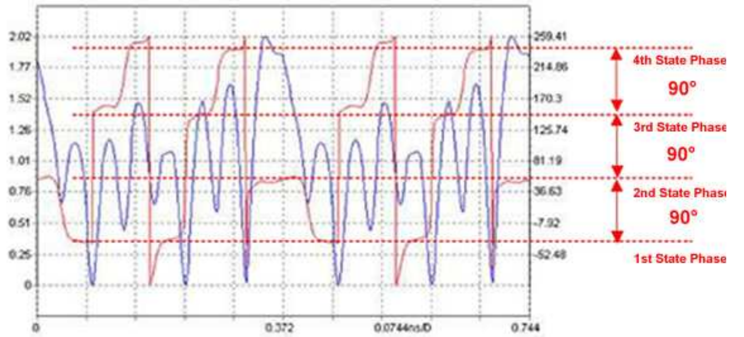


Figure 12: 40 Gb/s QPSK modulation measured by the Optical Complex Spectrum Analyzer

✓ Polarization diversity

Polarization multiplexing is also used to improve transmission spectral efficiency. In this case, independent signals are simultaneously transmitted on two orthogonal polarizations. One of the most important OCSA features is the OCSA's polarization diversity design. Indeed, the OCSA is able not only to combine the two orthogonal polarization states (polarization independent measurement) but also to display it separately. It is therefore possible to measure a polarization multiplexed signal.

✓ Optical spectrum analysis with ultra high resolution

The OCSA can be used as a normal optical spectrum analyzer but at a 100 times better resolution. With a 20MHz (0.16pm) resolution, 60dB@+/-2pm close-in dynamic range, +/-3pm wavelength accuracy, the OCSA is the perfect instrument for spectrum analysis (figure 13).

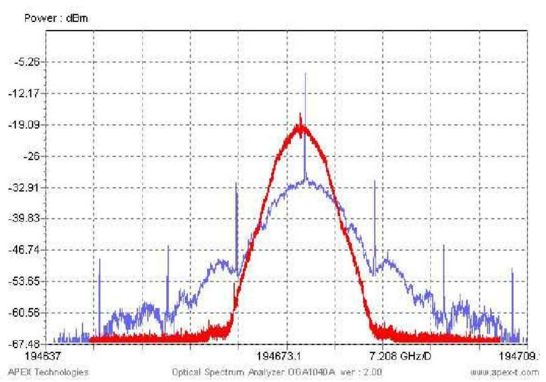


Figure 13: comparison between a 10 Gb/s OOK modulated signal (blue trace) and a 10Gb/s Duobinary modulated signal (red trace)

In addition to its spectral efficiency, ultra high resolution spectrum analysis provides a lot of other details (figure 14) on a modulated signal such as Crosstalk, laser linewidth, relaxation oscillations, and more.

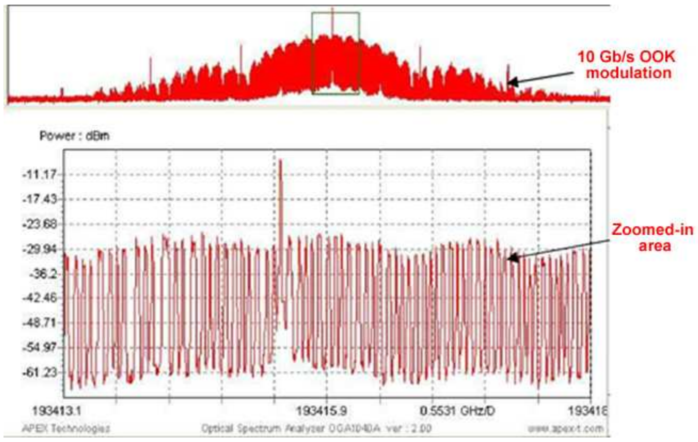


Figure 14: 10 Gb/s OOK modulated signal measured by the Optical Complex Spectrum Analyzer

Conclusion

The Apex Technologies Optical complex Spectrum Analyzer (OCSA) is the perfect tool for measuring any kind of optical modulation formats without any bit/baud rate limitation. The OCSA most important key features are:

- Time resolved intensity measurement with a > 6THz maximum bandwidth
- Time resolved chirp measurement with an high accuracy and repeatability
- Time resolved phase measurement for any kind of phase modulation formats
- Optical complex spectrum for chromatic dispersion measurement
- Optical spectrum analysis with ultra high resolution

All high speed modulation formats can now be accurately measured and leaves any kind of guesswork behind without the need for multiple instruments demanding a lot of space.

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