Resonant second harmonic generation using holey fiber for optical performance monitoring in DWDM networks

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Abstract: Optical second harmonic generation in dense wavelength division multiplexing (DWDM) was used to monitor the performance of each channel in all optical DWDM networks. A highly nonlinear photonic crystal fiber is used to convert C and L bands optical channels into half wavelength channels where silicon arrayed detectors and CMOS electronics were used to perform advanced digital signal processing to predict the optical channel presence, channel power, signal to noise ratio and the quality factor (Q) parameter. With further processing, the bit error rate per channel can be estimated from the Q factor.

Keywords: nonlinear, holey fiber, all optical networks, fiber measurements

Classification: Photonics devices, circuits, and systems

References


1 Introduction

Present optical communication systems require optical-electronic-optical (O-E-O) conversion for nearly all operations in the network which is not only expensive, but also restrictive; it prevents optical transparency, discards many of the attributes of optical signals, such as phase, frequency, polarization, and prohibits the use of some of the advantages of optics, such as ultrafast processes on picoseconds and sub-picoseconds time scales. Our approach aims at making compact, efficient and functional subsystems that can perform as many functions as possible such as real time optical performance monitoring (OPM) of complex all optical DWDM networks [1, 2]. Our prior work used poled Lithium Niobate (PP-LNO₃) for the second harmonic generation (SHG), however, it was shown that SHG conversion efficiency was low and new photonics bandgap fibers provide better conversion efficiency [3].

Optical signal to noise ratio (OSNR) is an important analog performance parameter that is often considered for performance monitoring of optical networks [4]. Since the optical filtering in optical add-drop multiplexers (OADMs) and optical cross-connects (OXCs) reshape the noise background, the interpolation of the noise background across the band can also be excluded by optical switching because each channel can acquire a unique noise background and therefore different OSNR. The parameters that most OPM systems measure directly are average optical power and wavelength. Typically the transmission fiber is tapped and a 5% or less of the signal power is extracted for further processing. From these direct measurements, a host of critical network performance parameters can be derived, such as channel presence verification, channel wavelength, amplified spontaneous emission (ASE) noise, optical-signal power, optical SNR (OSNR) per channel, optical-amplifier gain and gain tilt, and signal Q-factor from which the BER can be estimated [5]. These parameters may then be used to manage network reliability and define a quality of service for end users.

2 Nonlinear conversion

Our study explores novel techniques to find the best possible approach in order to develop integrated optical performance monitoring solution to realize transparency in optical networks. The specific device being used for second harmonic generation (SHG) is a highly nonlinear photonic crystal “holey fiber” which can be used for super continuum generation. The relation between the fundamental power and the second harmonic power for a photonic crystal fiber is given by [6].

\[
P_{2\omega} = \frac{8\omega^2 d_{eff}^2 P_{\omega}^2}{n_{2\omega}^2 n_{c}^2 \varepsilon_0^2 \varepsilon_0^3 A_{ovl}} \Delta \beta^2 \times \text{sinc}^2 \left( \frac{1}{2} \Delta \beta L \right)
\]
where $\omega$ is the fundamental frequency, $A_{ovl}$ is the overlap area between fundamental and second harmonic fields, $\Delta \beta$ is the wave vector mismatch, $d_{eff}$ is the effective nonlinear constant, $L$ is the length of the fiber, $n_\omega$ and $n_{2\omega}$ are the refractive indices of fundamental and second harmonic frequencies and $P_\omega$ and $P_{2\omega}$ are the fundamental and SH powers respectively. Using Eq. (1), the SH power and conversion efficiencies were plotted for different effective nonlinear constants as shown in Fig. 1. Conversion efficiencies of almost 30% can be achieved by carefully choosing the holey fiber. The holey fiber used for this purpose had a grating length of 6 cm and the fiber had a core size of 2 $\mu$m.

**Fig. 1.** Second harmonic power and Conversion efficiencies vs. fundamental power at fundamental wavelength of 1532 nm for different nonlinear coefficients

Figure 2 illustrates the principle of using SHG in performance monitoring. The output wavelengths $\lambda_1, \ldots, \lambda_n$ from a single fiber followed by erbium doped fiber amplifier were coupled to a nonlinear photonic crystal fiber. The optical path intercepted by a train of broad band dichroic beam splitters ($DM_n$) reflecting the SHG wavelengths.

**Fig. 2.** This sketch illustrates how SHG can effectively generate frequency doubling for optical DWDM networks: with minor broadening of data pulses Si-detector can provide system cost advantage over InGaAs detectors by detecting 775 nm instead of 1550 nm.
3 Digital signal processing on a chip

The OPM device with silicon detector arrays and high speed electronics were designed based on the number of elements necessary to meet channel-count requirements and optical resolution. The number of channels may be between 8 and 512 channels using commercial technologies available today. The pixel pitch used is between 25 and 250 microns depending on the array input optics. The main OPM device package consists of a detector chip on a ceramic sub-mount for possible integration with other networking devices, a glass-window hermetic package for easy handling and simple integration, or a hermetic fiber-pigtailed package with optical-fiber input for each detector pixel are included. Flip-chip back-illuminated arrays were used to avoid wire-bond clearance issues and incorporation of a thermoelectric cooler within the package for the lowest possible dark current and highest stability response.

Using an optical coupler, a small amount (5%) of light is tapped and passed through a tunable optical bandpass filter. The output of the filter is detected by a silicon photodiode that measures the signal power over the wavelength band sampled by the filter. The sampled value is further filtered by the digital signal processor (DSP) unit. We developed an advanced deconvolution signal-processing algorithm to extract data from the receiver. The firmware developed for the DSP unit handles signal processing of received data and performs real-time control for filter positioning. The filter is scanned using a technique that provides highly accurate and fast filter positioning over many cycles. A precision feedback system allows accurate measurement of the filter position in the wavelength domain. The filter is controlled using a dedicated microprocessor. Developing a real-time, closed-loop controller firmware to enable accurate sweep control of the filter is still underway. Separate coordinated processors are currently used to sample and filter optical power, and to control filter tuning. An independent host processor accepts user scan and setup commands, and displays the data acquired by the OPM device separately. The calibration software developed for the host computer incorporated compensation technique involving two-dimensional surface approximation techniques.

Of great interest, is the optical signal to noise ratio of the optical signal power in the primary data channel to the optical background noise accumulated during transmission and switching. It characterizes the ‘head room’ between the peak power and the noise floor detected at the receiver for each channel. It is an indication of the readability of the received signal and it is greatly affected by optical amplifiers in the span and may drop to about 15–20 dB at the end span for multi span networks. OSNR can be reduced by amplification, phase noise conversion and other effects. While measuring the OSNR can prove to be difficult because of the many aspects that contribute to noise in a given system; another important parameter the Q-factor, which can be easily measured. It is cumbersome when testing bit error rates (BER) lower than $10^{-16}$. Q-factor has become the new quality evaluation parameter to approximate the BER in a system. The Q-factor is a measure of the optical...
signal-to-noise ratio assuming Gaussian noise statistics. It is a quantitative measure of the eye quality. It can be thought of as the eye’s OSNR and can be derived from making measurements of BER as a function of “threshold” near the upper and lower rails.

![Fig. 3. Vertical cross-section of the eye-pattern, where the horizontal axis gives the received optical and electrical converted powers in mV and the vertical axes gives the chance of detection of a certain power. By using a Gauss fit-procedure, the positions of the peaks ($\mu_1$ and $\mu_0$) and standard deviations ($\sigma_1$ and $\sigma_0$) of the peaks can be determined.](image)

In the initial measurement, the vertical cross-section of the eye-pattern, where the horizontal axes gives the received optical and electrical converted powers in mV and the vertical axes gives the chance of detection of a certain power shown in Fig. 3. By using a Gauss fit-procedure, the positions of the peaks ($\mu_1$ and $\mu_0$) and standard deviations ($\sigma_1$ and $\sigma_0$) of the peaks can be determined. The Q-factor can then be calculated using Eq. (2):

![Fig. 4. Histogram of the eye diagram of the 2.5 Gb/s pseudorandom signal detected by Si APD (a Q parameter of 6.8 was obtained for this experiment)](image)
The Q-factor depends on the difference of levels between the “0” and the “1” and on the noise on the bit-pattern. So for a high Q-factor, the discrimination of the “0” and “1” is better than for a low Q-factor. Figure 4 shows the eye diagram and histogram detected by a Si APD and displayed on digital scope. The Q parameter for 2.5 Gb/s was measured at 6.8 which corresponds to a BER of $5.231 \times 10^{-12}$.

4 Conclusion

The application of second harmonic generation using holey fibers in all optical DWDM networks had been used for optical performance monitoring taking advantage of low cost silicon avalanche photodiodes and high speed digital signal processing electronics in CMOS technology. Using electronic sampling, all necessary performance monitoring parameters can be provided which allows systems vendors to guarantee various levels of quality services. Initial experimental measurements are very promising and we plan to follow with more detailed results. A low cost performance monitoring tool fabricated in CMOS technology allows optical transparency as well as wider deployment of all optical networks.