

Linear and Nonlinear Crosstalk Evaluation in DWDM Networks Using Optical Fourier Transformers

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A novel DWDM channel monitoring technique based on the conversion from wavelength domain to time domain by performing a real-time optical Fourier transform over the whole DWDM system bandwidth is proposed and experimentally demonstrated. The use of chromatic dispersion-based optical Fourier transformers has been validated in the case of a spectrum comprising light from different uncorrelated sources. Linear and nonlinear crosstalks between the DWDM channels appear as amplitude noise at specific time positions. The correspondence of this amplitude noise with the crosstalk spectral distribution is evaluated theoretically and experimentally.

Keywords and phrases: crosstalk monitoring, optical Fourier transform, optical signal processing, DWDM transmissions, ultra-high-speed optical transmissions, OTDM.

1. INTRODUCTION

The increasing demand for higher transport capacity in DWDM core networks can be fulfilled with different complementary approaches: by increasing the number of channels, increasing the transported bit rate per channel or decreasing the channel spacing. The later two approaches lead to an augment of the spectral efficiency of the DWDM network. As the spectral efficiency increases, the crosstalk between the DWDM channels arises as important transmission and also node functionality impairment. Next generation DWDM networks operating at ultrahigh bit rates, that is, 160 Gbps per channel, require precise channel transmission quality assessment systems inside the network infrastructure. For this reason fibre link condition and optical node functionalities have to be carefully monitored in order to enable ultracapacity (greater than 10 Tbps) all-optical DWDM networks [1].

From the network node point of view, second-generation all-optical nodes are especially susceptible to crosstalk [2, 3] which is accumulated at each node along the optical path [4]. Crosstalk in the optical node can be classified as either heterodyne (crosstalk between signals at different wavelengths) or homodyne (crosstalk between signals at the same nominal wavelength, also known as in-band crosstalk). Homodyne crosstalk can be further subdivided into homodyne coherent crosstalk, if it is produced between phase-correlated signals, and homodyne incoherent crosstalk, if produced between signals which are not phase-correlated [3]. The most important noise contribution in the optical node is the homodyne noncoherent crosstalk [3, 4]. This noise is originated inside the network node due to nonperfect blocking of channels at the same nominal wavelength during channel extraction, multiplex, demultiplex, or channel wavelength conversion operations. This crosstalk is incoherent, since it is originated by a different channel and

cannot be eliminated once generated. This incoherent homodyne crosstalk exhibits the same spectral power distribution present in any DWDM channel in the system and has to be properly monitored in order to guarantee node operation. Regarding the possible presence of additional homodyne intrachannel coherent crosstalk (originated by channel power leaking and propagation by different paths inside the optical node), it does not possess a real problem since the difference between the light paths inside the network node is usually longer than the coherence length of the laser source [4].

In the DWDM network the optical nodes are connected by optical transmission links. In order to reach maximum transport capacity, it is necessary to combine tight channel spacing and compact-spectrum modulations [5]. The link capacity limiting factor is the optical bandwidth of the transmission amplifiers. Commercially available erbium doped fibre amplifiers (EDFA) allow a usable bandwidth of 30–40 nm. To achieve bandwidths larger than 80 nm, novel amplifier architectures based on hybrid Raman amplification/erbium, tellurite doping, or hybrid Raman amplification/tellurite have been proposed [6] but these technologies are not readily available. Ultra-high-capacity DWDM networks require to fit the maximum number of channels in the amplifier bandwidth, which in turn require the use of spectrally efficient modulations like single sideband (SSB), vestigial sideband (VSB), nonreturn to zero (NRZ) or optical duobinary, or compact-spectrum modulation like carrier-suppressed return to zero (CS-RZ), alternate polarization RZ (AP-RZ) or alternate chirp RZ (AC-RZ), and/or polarization interleaving between the different WDM channels [5, 7]. Under these circumstances (close packaging of the WDM channels and compact spectrum of the DWDM channels) crosstalk monitoring is a key element for the optical link reliability as transmitter, or optical path degradation will impact the link availability very quickly [1].

Crosstalk in the optical link arises from different sources: linear crosstalk between adjacent DWDM channels due to insufficient channel spacing, nonlinear crosstalk arising from the wavelength interaction due to the fibre nonlinearities, and also intrachannel time crosstalk produced by the pulse broadening when pulses propagate along the dispersion map of the transmission link. Linear crosstalk is important as the degradation of network equipment, channel central frequency shift due to temperature drift in DFB-LD lasers, or degradation in optoelectronic transmitters will strongly impact the performance if tight channel spacing is used [7]. Nonlinear crosstalk is produced in the DWDM link from nonlinear effects mainly four-wave mixing (FWM) between different channels [8]. This effect although mitigated by the dispersion map is enhanced when the channel separation is very tight and nonuniform channel spacing can not be used [8, 9].

In the case of intrachannel crosstalk, this noise is due to cross-phase modulation (XPM) and four-wave mixing in the time domain. Time-domain FWM is reflected in amplitude fluctuation as reported in [10]. In dispersion-managed

transmission links with small average dispersion this noise increases with distance and its mitigation requires the use of loss compensation by means of Raman amplification. In the case of intrachannel XPM this is reflected in a mean frequency shift of the pulses which is translated to timing jitter through fibre dispersion [11]. If negligible average dispersion is achieved along the transmission link, this effect is suppressed [11, 12]. This is the particular case of ultracapacity DWDM networks. Transmission at 160 Gbps channel bit rate requires that the optical link between nodes be carefully planned in advance as pointed out in the small number of trials performed over actual SSMF [13]. The dispersion map used requires extremely low residual dispersion (1.2 ps/nm max. deviation for 160 km SSMF transmission) and also dispersion slope compensation [14]. It is also worth noting that the complete chromatic dispersion compensation along the system makes the accumulated chirp in the pulses negligible [12].

Common channel monitoring techniques rely on the use of arrayed-wavelength gratings (AWG) [15], Fabry-Perot filters [16], acousto-optic tunable filters [17], or tunable active filters [18] in order to separate the different WDM channels and to evaluate the channel noise power in absence of transmitted power, that is, stopping the channel operation. Other nondisruptive techniques propose the use of pilot sideband tones besides the digital data spectrum in order to evaluate the degradation of the transmitted information for each wavelength [19]. This method lacks transparency through the optical network nodes, like optical add-drop multiplexers (OADM) and optical cross-connects (OXC), as the pilot tones are eliminated after regeneration inside the network element. Another technique proposes the use of low-speed modulated signals overimposed on the main bit stream [20]. This technique requires the use of specific modulation and demodulation systems which can increase system complexity.

Our target is to monitor the crosstalk level in the DWDM network node either if it is originated inside the node or in the transmission link. The herein proposed system is based on optically time gating the DWDM signal during a specific time duration (one-bit time-slot) and to perform a continuous optical Fourier transform (OFT) comprising the whole set of transmitted wavelengths. This approach does not require to stop the channel operation. Once the spectral information has been brought to time domain, the basic parameters such as amplitude (channel power) or central wavelength can be evaluated. The key advantage of the proposed technique is that, additionally, it is feasible to evaluate the crosstalk spectral distribution (the interfering optical power distribution with frequency) that any DWDM channel is suffering. This is accomplished by the real-time OFT operation. Once the spectral data is in the time domain, it is photodetected and sampled to be postprocessed. In presence of crosstalk, the samples captured exhibit a uniformly distributed noise at specific time positions. By measuring the noise power and the noise time position we can evaluate the crosstalk level and the crosstalk spectral location, respectively.

The crosstalk spectral distribution gives us more information than the total crosstalk figure in dB usually given in crosstalk measurements. The knowledge of the spectral distribution opens up the opportunity to identify the crosstalk source, that is, if it comes (in the case of linear crosstalk) from the channel at the right or at the left. It is clear that if the crosstalk source is an adjacent channel, its spectral distribution will be at one side of the channel spectrum. If it is originated by nonlinear crosstalk due to FWM (evenly spaced channels), then the noise spectral maximum will be at the central frequency of the crosstalk channel. In this case, once the crosstalk type is identified, we can correlate the presence of crosstalk in a specific channel with the presence of power in a given set of channels. This correlation allows us to identify the crosstalk origin channels.

As discussed before, the OFT is the key operation of the proposed system and it is performed over the whole optical system bandwidth. The OFT operation is implemented here by means of a dispersive element. The use of chromatic dispersion effect in standard single-mode fibre (SSMF) to convert the spectral information to time domain has been previously reported in [21, 22]. Linearly chirped fibre Bragg gratings (LCFBG) have been also proposed as dispersive elements capable of performing this operation [23]. The Fourier transformers using SSMFs give the advantage of nearly no bandwidth limitation, which makes this approach especially interesting for large-channel-count DWDM systems. The use of dispersive devices in real-time spectrum analysis systems was proposed for DWDM systems in [21] and experimentally demonstrated for a phase coherent spectrum [24] (coherency means here that all the lights present at the spectrum have the same phase reference, i.e., the whole spectrum comes from only one optical source). Actual DWDM systems, however, exhibit lack of phase coherency between the different WDM channels as they come from different optical sources. This lack of spectral coherency leads to the presence of an amplitude noise after the OFT that depends on the crosstalk level. The amplitude noise power level gives us information about the crosstalk level that the channel under evaluation is suffering from the rest of the WDM channels. This correspondence will be evaluated in the next section.

Another interesting feature of the proposed OFT approach is the time expansion effect introduced by the dispersive element. In the proposed system, the output from the OFT cell is a time-stretched version of the Fourier transform of the input signal envelope. This expansion in time is a convenient feature as it is possible to use commercially available electrical analog-to-digital conversion (ADC) circuitry in order to capture (convert the electrical photodetected signal to digital data) the spectrum and to postprocess the results.

2. PRINCIPLE OF OPERATION

We consider a generic crosstalk situation in a DWDM network employing Gaussian RZ modulation. The network uses K channels (wavelengths) with channel spacing Δ (rad/s). In conventional DWDM networks the channel separation Δ is

wide enough so that the spectral overlap between the channels is negligible. This is not the case of high-spectral efficiency networks where the adjacent channel power can leak due to not perfect channel filtering at multiplexing stage, during channel extraction operation or because of transmitter degradation.

In the general case, for the sake of simplicity we will consider that the DWDM channels are evenly spaced around a central angular frequency ω_0 so the central angular frequency for the k th channel is $\omega_0 + \omega_k = \omega_0 + \Delta \cdot k$, where $k = -(K-1)/2 \dots (K-1)/2$. This DWDM spectral space can be described by equation (1), where $s_A(t)$ is the bit-synchronised received optical complex field envelope around the central angular frequency of the DWDM transmission system (ω_0). The channels are considered synchronised in time as this is the worst-case crosstalk scenario. In equation (1) A_k stands for the optical field amplitude and $b_{k,n}$ is the transmitted data (mark or space) by the channel k in the n th-bit time-slot. The parameter T_k stands for the Gaussian pulse half-width at $1/e$ fall from peak. $R = 1/T_b$ is the system bit rate. Figure 1 shows the DWDM system in a bidimensional space (angular frequency, time) described by

$$s_A(t) = \sum_k \sum_n A_k b_{n,k} \exp(j\omega_k t) \exp\left[-\frac{1}{2}\left(\frac{t - nT_b}{T_k}\right)^2\right]. \quad (1)$$

Our analysis targets crosstalk evaluation in a generic network node. Such node, optical add-drop multiplexer (OADM) or optical cross-connect (OXC), is depicted in Figure 2 (top diagram). This generic node can perform DWDM insertion/extraction or wavelength conversion whether it is an OADM (optical add-drop multiplexer) or an OXC (optical cross-connect). The channel monitoring block is shown before the node operation, controlling a channel equalizer and monitoring the crosstalk introduced in the link. This block can be placed inside the node or directly in the transmission link sending information through a supervisory channel.

The proposed DWDM crosstalk monitoring system architecture is shown in Figure 2 (bottom schematic). The system consists of a gating switch which selects only one bit period (T_b time duration) of every N bits. This gating switch can be implemented in the optical domain by using saturable absorbers [25, 26], interferometric devices like the nonlinear optical loop mirror (NOLM) [27] and the ultrafast nonlinear interferometer (UNI) [28], or a Mach-Zender architecture employing semiconductor optical amplifiers (SOA) [28]. These devices can work at 160 Gbps core network line rates. The purpose of the gating switch is to select only one bit-slot of every N bits (one bit-slot contains only one bit from all the wavelengths of the DWDM system as the optical gate does not impose any bandwidth limitation) and to feed it into the OFT cell which performs an optical Fourier transform. The exact value of N depends on the chromatic dispersion of the OFT cell as will be discussed later. This gating can be performed in a continuous basis or every time that a channel monitoring is desired. Equation (2) describes

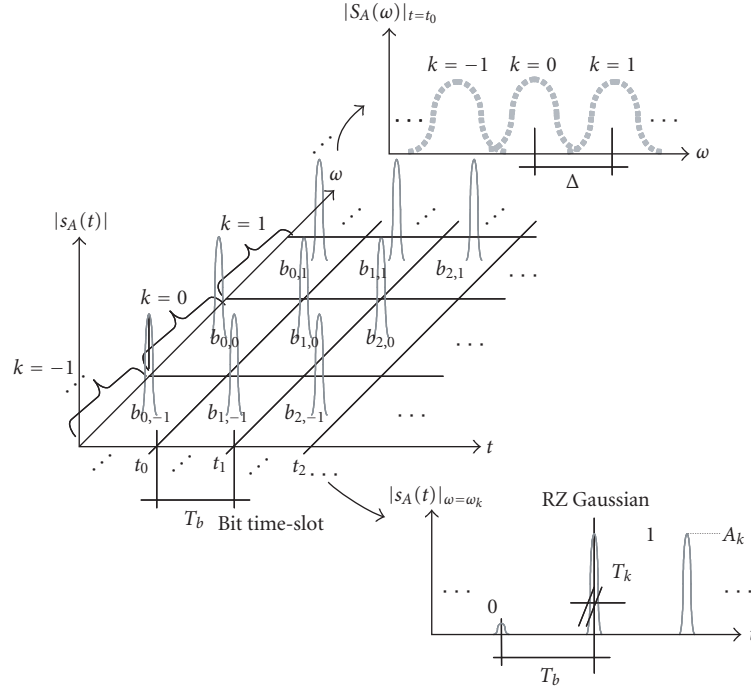


FIGURE 1: Bidimensional (angular frequency, time) DWDM space in modulus, $|s_A(t, \omega)|$. Gaussian RZ signaling is used. A spectrum cut (in modulus) $|s_A(\omega)|_{t=t_0}$ is shown on top for a given time t_0 . This spectrum comprises K wavelengths with Gaussian shape. The time signal (in modulus) is also shown (bottom) for a given channel k . The optical Fourier transform operation is performed over the T_b bit time-slot shown.

the complex field envelope after theoretical gating of an arbitrary n th bit and its Fourier transform. The time reference has been placed in the centre of the pulse to simplify calculations. After the optical gating, one bit of the DWDM channels is fed to the Fourier transformer to bring the spectral information into the time domain. Once in time domain this spectrum is sampled at R_s rate:

$$s_{B,n}(t) = \sum_k A_k b_{n,k} \exp(j\omega_k t) \exp\left[-\frac{1}{2}\left(\frac{t}{T_k}\right)^2\right], \quad (2)$$

$$S_{B,n}(\omega) = \sum_k A_k b_{n,k} T_k \sqrt{2\pi} \exp\left[-\frac{1}{2}(\omega - \omega_k)^2 T_k^2\right].$$

In Figure 3 the gating and optical Fourier transform process is shown in detail. As mentioned before, at the output of the OFT cell, the spectral information is obtained as a time signal. Therefore, we have performed the spectrum-to-time conversion of one time-slot comprising the whole set of K wavelengths of the DWDM system. The time signal at the output of the OFT cell [23] is described by (3). The output pulses width depends on the first-order dispersion coefficient $\ddot{\Phi}$. The pulses amplitudes involve the factor L standing for the OFT device optical losses. This signal is then photodetected and converted from electrical continuous signal to digital data in order to evaluate the spectrum.

This conversion can be performed by a commercial ADC:

$$s_{C,n}(t) = L \cdot \exp\left(-\frac{jt^2}{2\ddot{\Phi}}\right) \{\text{FT}[s_B(t)]\}_{\omega=t/\ddot{\Phi}}$$

$$= L \cdot \exp\left(-\frac{jt^2}{2\ddot{\Phi}}\right) S_B\left(\frac{t}{\ddot{\Phi}}\right)$$

$$= L \cdot \exp\left(-\frac{jt^2}{2\ddot{\Phi}}\right) \times \sum_k A_k b_{n,k} T_k \sqrt{2\pi} \exp\left\{-\frac{1}{2}\left[\frac{(t - k \cdot \Delta \cdot \ddot{\Phi})^2 T_k^2}{\ddot{\Phi}^2}\right]\right\}. \quad (3)$$

From (3), if the dispersive element presents a first-order dispersion coefficient of $\ddot{\Phi} = -\partial^2 \Phi / \partial \omega^2$, the resulting time signal after OFT comprises Gaussian shape pulses (as corresponds to the Fourier transform of a Gaussian pulse) of width $\ddot{\Phi}/T_k$ separated in time by the factor $\Delta \cdot \ddot{\Phi}$. Each channel spectrum outputs from the OFT cell with $k \cdot \Delta \cdot \ddot{\Phi}$ separation. The time necessary to output all the wavelengths of the DWDM system is $K \cdot \Delta \cdot \ddot{\Phi}$. The gating ratio N must be high enough to produce a complete operation, so N has to be larger than $K \cdot \Delta \cdot \ddot{\Phi}/T_b$, where T_b is the system bit period. By photodetecting and sampling $s_{C,n}(t)$, we can evaluate the spectrum from the K system

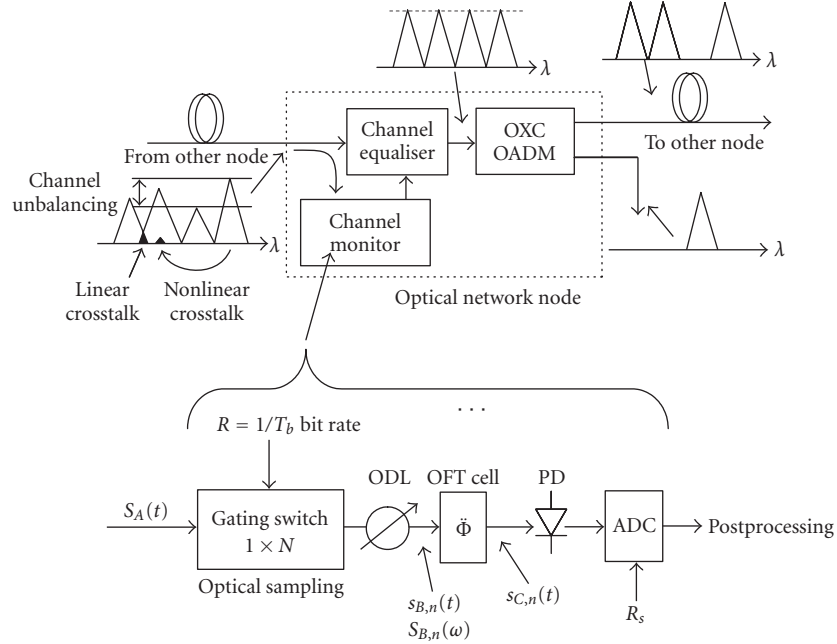


FIGURE 2: Top diagram shows generic network node structure. Proposed channel monitoring system architecture based in OFT operation using SSMF is shown in the schematic (bottom).

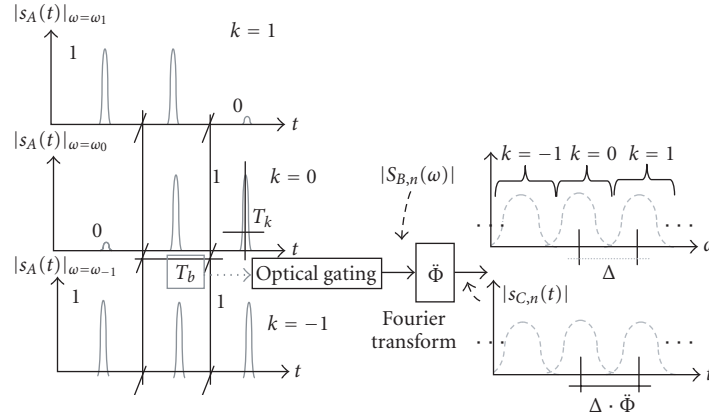


FIGURE 3: Channel monitoring principle of operation: T_b time-slot id-gated and fed to the optical Fourier transformer. After Fourier transform we obtain the spectrum components in time domain.

channels. The minimum sampling rate should allow one sample per channel, that is, $R_{s,\min} = 1/(\Delta \cdot \Phi)$. After OFT, photodetection, and sampling, given the spectrum information, we can evaluate the channel amplitude (power) level, the channel separation (time difference between power peaks), and the crosstalk the channel is suffering, as will be discussed later. By example, the use of a commercial ADC with a sampling rate of 800 Msps (readily available from different vendors) leads to 1.25 nanosecond temporal resolution. The accumulated dispersion from 150 km SSMF ($-19\,296$ ps/THz) OFT gives a spectral resolution (frequency

separation between samples) as low as 64 GHz. To achieve a fine sampling of the spectrum envelope, the proposed system includes an optical delay line (ODL) shown in Figure 2 which delays the input to the ADC in a computer-controlled way. Sweeping the optical delay, the different points of the DWDM spectrum will be sampled and we can reconstruct its shape completely. The sampled waveform corresponds to a spectral-domain to time-domain conversion taking place, and the power overlapping in the spectrum will appear as an amplitude noise in the Gaussian pulses after Fourier transform.

In order to characterize the noise in the time domain, we will evaluate now the output from the OFT when two generic wavelengths with Δ channel separation overlap to some extent in spectrum: we consider two adjacent DWDM channels, k and $k + 1$, bearing Gaussian RZ pulses in the DWDM system of amplitude A_k and A_{k+1} and pulse width T_k and T_{k+1} , respectively. This is a general case from equation (2) where the interaction of any two channels is evaluated. This generic situation can be particularized for different kinds of crosstalk described in the previous section. For linear crosstalk, the noise origin is the spectrum overlap from the adjacent channel, the spectral separation between lights of channel k and $k + 1$ is the channel spacing $\Delta \gg 0$, and the amplitudes A_k and A_{k+1} will be in the same order of magnitude, $A_k \approx A_{k+1}$. In the case of nonlinear crosstalk, the noise origin is another channel which, due to nonlinear effect like FWM, appears spectrally overlapped (the channels are equally spaced) exactly at the centre of the channel under study k . In this case the spectral separation between channel k and the interference $k + 1$ is negligible $\Delta \approx 0$, but due to limited FWM efficiency, the interference amplitude will be much lower $A_{k+1} \ll A_k$.

Following the general analysis, the channels k and $k + 1$ come from different optical sources through different optical paths. As these channels are mutually noncoherent, the optical phase difference is considered by the term ϕ which is a uniformly distributed random variable. Then, the complex optical envelope $s(t)$ and spectrum envelope $S(\omega)$ for channels k and $k + 1$ can be written as

$$\begin{aligned} s_k(t) &= A_k \exp(j\omega_k t) \exp\left[-\frac{1}{2}\left(\frac{t}{T_k}\right)^2\right] \\ &\xrightarrow{\text{FT}} A_k T_k \sqrt{2\pi} \exp\left(-\frac{1}{2}((\omega - \omega_k)T_k)^2\right) \\ &\triangleq S_k(\omega), \\ s_{k+1}(t) &= A_{k+1} \exp[j(\omega_k + \Delta)t + j\phi] \exp\left[-\frac{1}{2}\left(\frac{t}{T_{k+1}}\right)^2\right] \\ &\xrightarrow{\text{FT}} A_{k+1} T_{k+1} \sqrt{2\pi} \\ &\quad \times \exp\left(-\frac{1}{2}((\omega - \omega_k - \Delta)T_{k+1})^2\right) \exp(j\phi) \\ &\triangleq S_{k+1}(\omega) \exp(j\phi), \end{aligned} \quad (4)$$

where A_{k+1} , ω_{k+1} , and T_{k+1} stand for the optical field amplitude, the central angular frequency, and the pulse width at $1/e$, respectively, for wavelength $k + 1$. From (3), after the Fourier transform element we have the combination of both spectra:

$$s'_c(t) = L \cdot e^{-jt^2/2\Phi} \cdot \{S_k(\omega) + S_{k+1}(\omega) \exp(j\phi)\}_{\omega=t/\Phi}. \quad (5)$$

The term $L \cdot e^{-jt^2/2\Phi}$ is a complex constant whose phase will be lost after photodetection. The photodetected signal at the

OFT output is proportional to the optical intensity $I_{\text{out}}(t)$ as described by (6). This intensity corresponds to the combination of the wavelengths k and $k + 1$ power spectra with noise

$$\begin{aligned} I_{\text{out}} &\sim |S_k(\omega) + S_{k+1}(\omega) \exp(j\phi)|_{\omega=t/\Phi}^2 \\ &= S_k^2\left(\frac{t}{\Phi}\right) + S_{k+1}^2\left(\frac{t}{\Phi}\right) + n(t). \end{aligned} \quad (6)$$

The noise $n(t)$ involves the random variable ϕ which is the phase difference between both wavelengths at any time position. Except for if both lights are provided by the same optical source and are guided through the same optical path, we can only say that ϕ adopts a random value between $-\pi$ and π with uniform distribution. This noise is a random process and is described by equation (7). Every time a channel estimation is done, we obtain one realization of the process. For simplicity, the realization number is not shown in

$$n(t) = 2S_k\left(\frac{t}{\Phi}\right)S_{k+1}\left(\frac{t}{\Phi}\right)\cos(\phi). \quad (7)$$

From (7) the OFT output at any specific time position t_i , that is, $n(t_i)$, is a random variable. This random variable will fluctuate according to the random nature of the phase difference ϕ . The noise variance (fluctuation) for time position is given by (8) and shows that the noise power in time domain follows (except by a proportionality factor) the optical spectrum overlap $S_k(t_i/\Phi)S_{k+1}(t_i/\Phi)$:

$$\sigma_{n,t_i}^2 = 4\pi S_k^2\left(\frac{t_i}{\Phi}\right)S_{k+1}^2\left(\frac{t_i}{\Phi}\right). \quad (8)$$

Equation (8) reflects that the noise power at the specific time position t_i depends only on the crosstalk at the specific spectrum angular frequency $\omega_0 + t_i/\Phi$. Sweeping the time position t_i , we sweep over the complete spectral range. In this way, accumulating the samples for any time position t_i , we can evaluate its mean and variance for the corresponding frequency. The variance represents the crosstalk noise as this is produced by the crosstalk (if no crosstalk is present, no variance can be observed) as is discussed in the next section. In this way we can calculate the crosstalk spectral distribution. This result is difficult to achieve with current spectrum analysis techniques and is enabled by the feasible real-time Fourier Transform operation proposed in [21].

The crosstalk spectral distribution gives us total crosstalking power (noise integrated over the channel under study bandwidth) and, from the envelope of the noise spectral distribution, we can identify the crosstalk nature: if it is located at one side of the channel bandwidth, then the origin is linear crosstalk from the adjacent channel as is demonstrated in the experimental work in the next section. If the noise distribution is centered in the channel bandwidth under study and follows the Gaussian power profile, then the

source is nonlinear FWM (provided the channels are equally spaced). In this case, performing a statistical correlation of this noise with the presence of power (marks) transmitted in any other DWDM channel, we can identify the crosstalk source.

This result can be extended to more than two interfering channels: we evaluate now the influence of multiple channels interfering a given channel k . Noncoherent crosstalk, which means that the interfering channels are uncorrelated, will be reflected again as the power spectrum overlap. In the case of M interferers over the k th channel, the noise from any channel of the system will also be additive in power. Equation (9) is an generalization of equation (8) for the interaction of channel m over channel k :

$$\sigma_{k,m,t_i}^2 = 4\pi S_k^2 \left(\frac{t_i}{\Phi} \right) S_m^2 \left(\frac{t_i}{\Phi} \right). \quad (9)$$

The total noise power, if M channels affect, will be given by (10), as the different $n_{k,m}^2(t)$ for each m interfering channel are uncorrelated noise processes for each m channel as the channels are not mutually coherent:

$$\sigma_{k,M,t_i}^2 = \sum_M \sigma_{k,m,t_i}^2 = S_k^2 \left(\frac{t_i}{\Phi} \right) \sum_M S_m^2 \left(\frac{t_i}{\Phi} \right). \quad (10)$$

Equation (10) reflects that the total crosstalk noise spectral profile is the sum of the spectrum envelope overlaps of all channels $m \neq k$. In the case of channels with large frequency separation, its influence will be quickly dismissed, as the Gaussian spectral shape decays quickly. In the case of non-linear crosstalk, as mentioned at the beginning of the section, the channel separation is almost zero, but due to the low non-linear process efficiency the interference amplitude A_m will be much lower than the channel under study A_k . The particular FWM efficiency value depends on the particular dispersion and amplification map [9] of the system, and will be reflected in the A_m amplitude implicit in the term $S_m^2(t_i/\Phi)$ in (10).

3. EXPERIMENTAL RESULTS AND DISCUSSION

As a proof of concept, a set-up has been arranged to evaluate the proposed monitoring technique operation on two DWDM channels transporting Gaussian RZ pulses with strong linear crosstalk following the calculations in the previous section. This linear crosstalk is induced arranging the different channels with enough frequency overlap. If we would consider in-band crosstalk, we would simply overlap the wavelengths completely. The set-up is shown in Figure 4 and consists of two tunable mode-locked laser sources with a wavelength range of ± 12 nm around 1552 nm. The generated pulses are mutually noncoherent and exhibit $T_{FWHM} = 1.6$ picoseconds. This pulse width corresponds to 25% RZ signaling at 160 Gbps bit rate per channel. The repetition

rate is set to $R = 1.04150$ GHz using an external RF reference signal. A RF phase shifter was employed for fine tuning in order to vary the relative pulse positions. An optical delay line for coarse tuning may be also used, as shown in Figure 4. After combining both pulsed lights, the signal is passed through a dispersive device (OFT cell). In the experiment a coil of 2.1 km of SSMF was used, providing a total dispersion of $\Phi = -42.855$ ps²/rad, which is large enough to perform a successful Fourier transform, as it meets the condition $|T_b^2/\Phi| \ll 1$ reported in [23]. The large optical bandwidth of the fibre-based OFT cell presents the advantage of being wide enough to allocate the whole system bandwidth. This would be difficult to accomplish if a linearly chirped fibre Bragg grating was used for FT operation in a large WDM system, as the system bandwidth might exceed the grating bandwidth. Furthermore, the signal is photo-detected and monitored in the sampling scope.

Figure 5a shows the spectrum of two DWDM channels from the experimental set-up described above with channel spacing of 3.72 nm, whereas Figure 5b shows the output of the OFT cell after photodetection (electrical output). We can observe the good agreement between the optical spectrum at the input and the time electrical waveforms shape at the output, hence demonstrating the proper FT operation.

In order to evaluate the fibre-based Fourier transformer behavior in the presence of linear crosstalk, a strong wavelength overlap is introduced by getting closer (spectral spacing of 2.3976 nm) the DWDM wavelengths. Figure 5c shows the spectrum in this situation, whereas Figure 5d shows the output from the OFT cell. The presence of the predicted amplitude noise dependent on the linear crosstalk at the input is clearly shown as was expected from (7). If no crosstalk is present (e.g., $A_k = 0$) all the amplitude noise vanishes as can be seen in the insets (e) and (f) in Figure 5.

This amplitude noise (marked with the rectangle in Figure 5) is present only at the time positions where there was spectrum overlap in the frequency domain. In order to assess this correspondence, we have evaluated the accumulated noise after several successive OFT (channel evaluation) operations. Figure 6 shows the optical power spectrum overlap $4\pi S_k^2(\omega) S_{k+1}^2(\omega)$ over the electrical amplitude noise at OFT output $\sigma_{n,t}^2$. The correspondence of the spectrum overlap with the amplitude noise rms (noise power distribution over time) value shows good agreement, thus validating (8).

4. CONCLUSIONS

A novel channel monitoring technique for high-speed DWDM networks based on performing the Fourier transform with a simple dispersive element has been proposed and validated. Gaussian 1.6-picosecond pulses, typical in 25% RZ 160 Gbps transmission, have been used for demonstration purposes. Proper OFT cell operation has been demonstrated using 2.1 km of SSMF. Amplitude noise correspondence, after OFT operation and photodetection, with the optical spectral overlap (linear crosstalk) profile has been evaluated and experimentally validated.

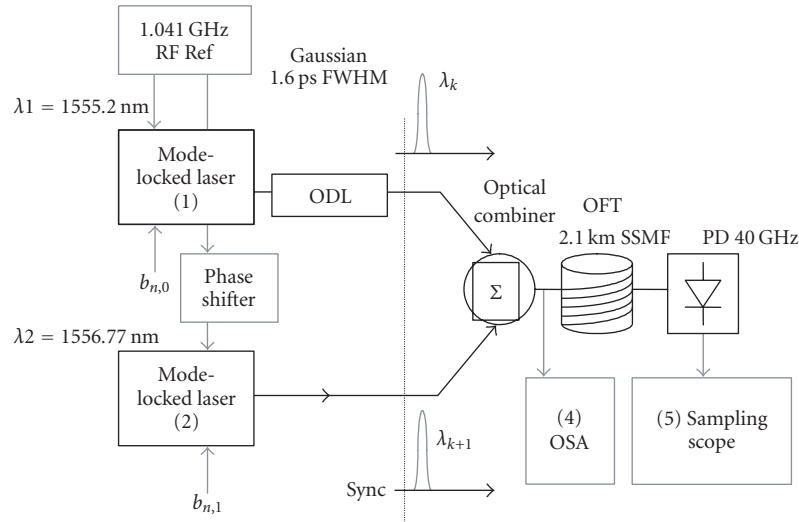


FIGURE 4: Experimental set-up. Combination of two nonmutually phase coherent 1.6-picosecond Gaussian RZ DWDM channels. OFT cell used comprises 2.1 km of SSMF.

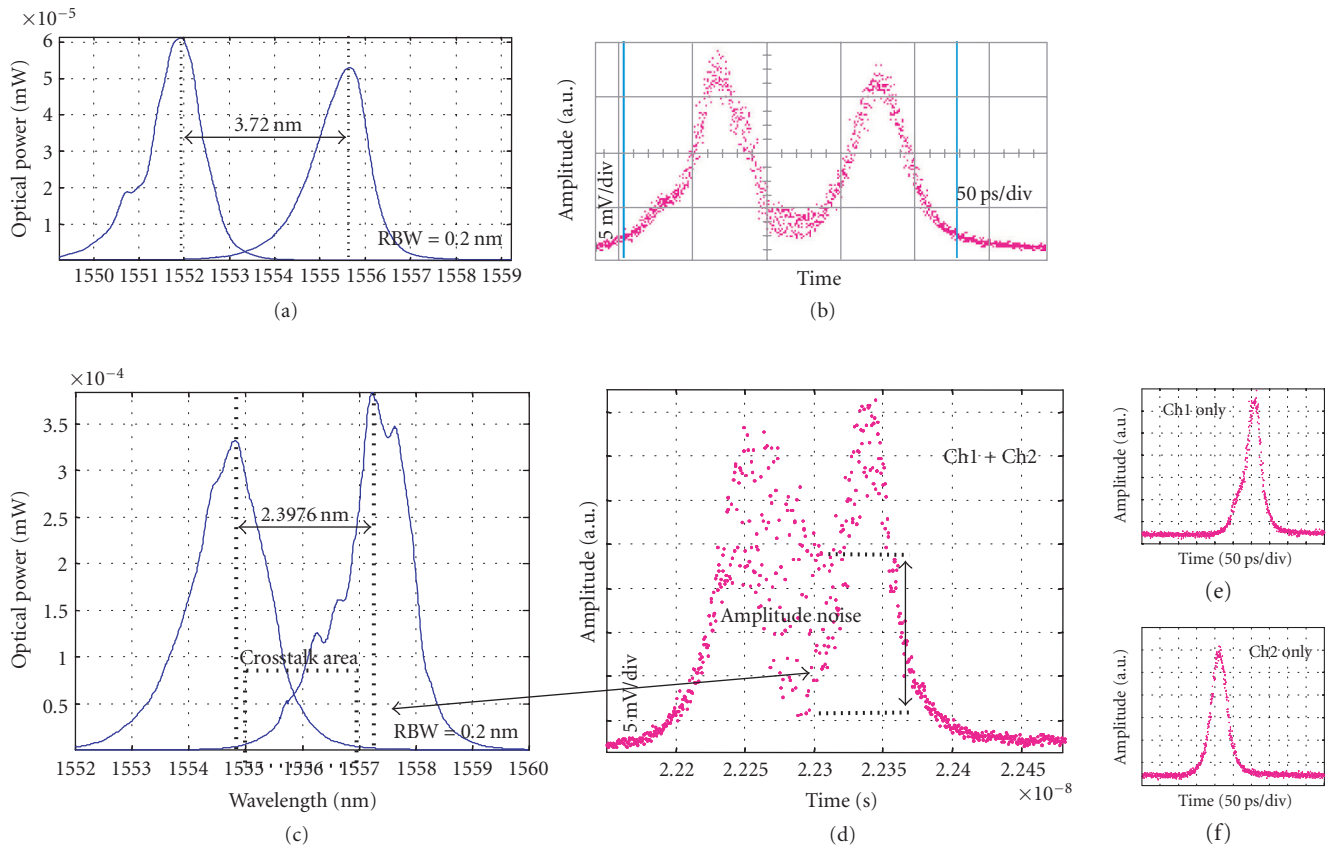


FIGURE 5: (a) Optical spectra at the input of the OFT cell. (b) Electrical signal after OFT and photodetection for 3.72 nm channel spacing. (c) Optical spectra with 2.3976 nm channel separation (11.62 dB crosstalk). (d) Corresponding electrical traces at the output of the OFT cell. Insets (e) and (f) show the two channels when no crosstalk is present.

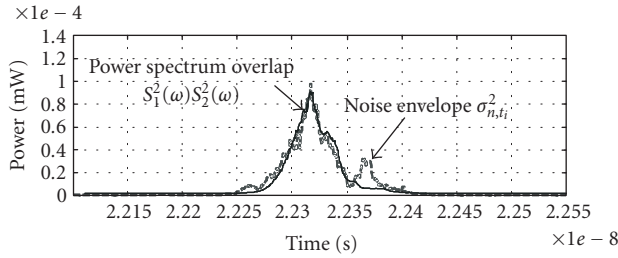


FIGURE 6: Optical power overlap profile at 2.3976 nm wavelength separation (solid line). Electrical amplitude noise power distribution envelope in time (dashed line).

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