2682

Novel Orthogonal Wavelength Division Multiplexing (OWDM) Scheme: Theory and Experiment

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Introduction

The continuous increase of the transmission capacity demand reveals particularly interesting new modulation and multiplexing techniques targeting at high spectral efficiency (bit/s/Hz) DWDM systems. Several approaches to augment the spectral efficiency have been proposed such as vestigial side-band demultiplexing [1], orthogonal polarisation multiplexing [2] and bandwidth limitation [3]. In the meantime, the orthogonal spectrum packaging of electrical carriers has proven its high spectral efficiency and resistance to transmission channel impairments in its electrical counterpart modulation, OFDM (Orthogonal Frequency Division Multiplexing). The electrical OFDM modulation is implemented using digital inverse Fourier-Transform (FT) operation in the transmitter and straight FT operation in the receiver. This approach can not be performed at the optical domain as digital signal processors are not available at core network line rates.

Optical orthogonal techniques have been proposed to enhance detector performance on heavily crosstalked channels in conventional DWDM channels [4]. In this paper, a novel orthogonal wavelength division multiplexing (O-WDM) modulation using Super-Structured Fibre Bragg Gratings as square pulse shaper followed by orthogonally interleaving the corresponding Sinc-function shaped spectrum of each channel is proposed and demonstrated at 10 Gbit/s. The results show that a significant reduction of the interchannel linear crosstalk penalty compared to conventional Gaussian RZ modulation.

Principle of operation

Let us consider an optical transmission system in which the signaling used comprise temporal square (field complex envelope) pulses of τ width, this means a sinc-shape spectrum (centered at $\omega = 0$ as reference) with deep nulls with separation $1/\tau$ in transform-limited condition. As discussed later, a proper orthogonal alignment of the WDM channels is achieved if the channel spacing is precisely set to $1/\tau$, as shown in Fig. 1. In this case, the linear crosstalk induced from channels at $\lambda_{\pm 1}$ and $\lambda_{\pm 2}$ (interfering channels) on λ_0 (channel under study) presents a deep power notch at the central frequency of wavelength λ_0. The above applies to all the system wavelengths, leading to evenly spaced deep crosstalk nulls at the centre wavelength (spectrum points marked λ_k in Fig. 1) of all the channels. Therefore, the orthogonal wavelength condition results in reducing the crosstalk level at the central wavelength of each channel. Using a sharp detection filter at the centre of the DWDM channel we would be able to reduce the linear crosstalk impact. Figure 1 reflects the theoretical power spectrum (log scale) for 5 wavelengths using 10 ps transform-limited square pulse signaling. The corresponding spectral separation is 100 GHz.

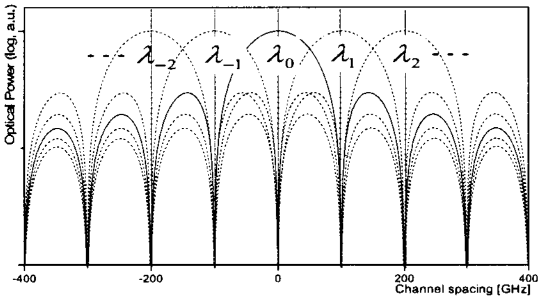

Figure 1.- Theoretical orthogonal spectrum multiplexing of 10 ps square pulses (channel spacing 100 GHz).

$$\int_0^{t_0+T} f(x)g(x)dx = 0 \qquad (1)$$

The channel spacing constrain arises from the mathematical orthogonality concept. Two functions are said to be orthogonal if they meet (1). Considering evenly spaced wavelengths around an arbitrary central wavelength λ_0, i.e. $f(t) = \exp(j\phi_1)$ is the un-modulated complex field envelope of the central wavelength λ_0. $g(t)$ corresponds to a wavelength λ_k separated ω_k [rad/s] apart from λ_0: $g(t) = \exp[j\omega_k t + \phi_2]$. Being τ the time square pulse width orthogonality holds only for specific Δ [Hz] channel separation:

$$\frac{1}{\tau}\int_0^{\tau} \exp(j\phi_1)\exp[j(\omega_k t + \phi_2)]dt = \qquad (2)$$
$$= \exp(j\omega_k \tau/2)\exp[j(\phi_1 + \phi_2)]\mathrm{sinc}(\omega_k \tau/2\pi)$$

a zero value for the argument of the sinc function above is obtained only if the channel separation is set to $\omega_k = |2\pi k/\tau| = |2\pi k \cdot f_0|$ (k integer). The orthogonality is guaranteed only if the channel separation $\Delta = \omega_{k=1}/2\pi$ is k times the inverse of the pulse width $1/\tau$. The spectral efficiency for this multiplexing scheme (without including polarization division or other techniques) is achieved for the lowest value $k = 1$, leading to 1 bit/s/Hz spectral efficiency.

Feasibility demonstration

In order to verify the proposed technique we performed experiments using orthogonal multiplexing of 3 WDM channels with 9 ps square pulses signaling. The set-up is shown in Figure 2. This line signaling may be scale up to 100 Gbit/s if 10 OTDM channels were aggregated per wavelength, because the low ISI due to the sharp edges of the square pulses used. In our set-up the repetition rate was 10 GHz.

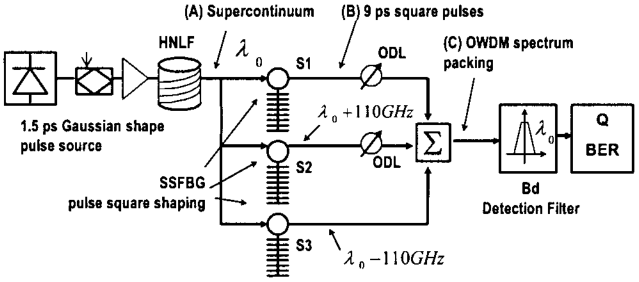

Figure 2. OWDM set-up.Orthogonal multiplexing of 3 channels in back-to-back configuration. Direct intensity detection.

The set-up comprises one mode-locked source generating Soliton pulses. The Soliton pulses were amplified up to +14 dBm and further fed to 500m of HNLF with non-linear coefficient $\gamma = 18(\mathrm{km}\cdot\mathrm{W})^{-1}$. To generate the three wavelengths, the supercontinuum is spectrally sliced with three tunable pulse-shaping SSFBG at 1550.6nm (S1), 1550.6 + 0.85nm (S2) and 1550.6-0.85nm (S3). This time square shaping produces a sinc shaped spectrum.

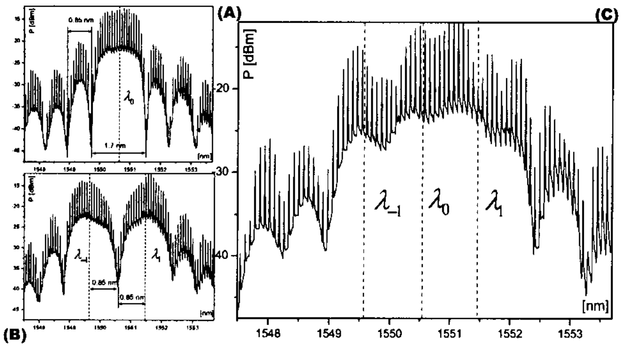

Figure 3.Inset (A), spectrum of central wavelength (B) The overlap spectrum of the 2 side interfering channels. (C) The composite spectrum with the Orthogonal Multiplexing.

After pulse shaping the 3 channels were orthogonally wavelength multiplexed, i.e. aligning the spectral peak of one channel with the nulls of the adjacent channels. Two tuneable optical delay lines (ODL) are used to allow full synchronization (worst interference case) and to decorrelate the data between channels. The spectra are shown in Fig3. Inset A shows channel at λ_0. The peak-to-first-null separation is 0.85 nm (110 GHz). Inset B shows the adjacent interfering channels at λ_{-1} and λ_1 orthogonally overlapped (wavelength separation of 1.78 nm). The three channels composite spectrum is shown in inset C. In order to recover the data we use a conventional direct detection technique using a narrow (0.2 nm) grating filter and a high-speed photo-detector. The detection filter bandwidth is a key parameter of this modulation scheme. The crosstalk nulls in the center of the WDM channels are very sharp, so a very narrow detection filter would reduce the total crosstalk noise after the optical detection filter of bandwidth B_d. Nevertheless we faced a trade-off on B_d, as the crosstalk power will arise as a strong beat noise as B_d diminishes [5] even for low crosstalk levels. Current work is being carried out to tune up this detection scheme. In order to compare the power gain relative to conventional RZ signaling, SSFBGs (S1, S2 and S3) were substituted to a 1.4 nm bandpass filters to fit 4 ps Gaussian pulses at 10 ps bit slot.

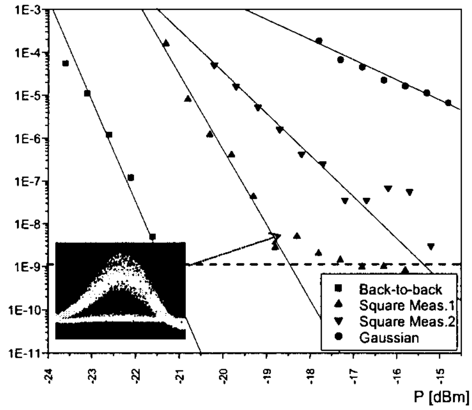

Figure 4.- Comparative BER results for 3 channels OWDM with 0.85nm separation. Two different OWDM measurements (triangle) using 9 ps square-shaped pulses. Gaussian RZ with 4 ps Tfwhm is shown for comparison (square) and residual set-up error (square)

Figure 4 shows the measured BER. The supercontinuum generation leads to the strong coherency between the WDM channels. The strong wavelength overlap leads to high sensitivity of the measurements on external conditions influencing the optical phase evolution in the three arms of the set-up, as temperature or vibration. Figure 4 shows two measurements with a 30 minutes difference. BER was integrated on 50s to avoid spurious results. Moreover, a BER error floor below 1e-9 BER which is due to the spectrum shape divergence with the theoretical Sinc shape and also because of the detection system sensitivity was limited. The crosstalk induced power penalty is sharply reduced over the conventional Gaussian RZ modulation.

Conclusions

A novel orthogonal multiplexing of WDM channels to increase the spectral efficiency and to reduce wavelength interaction and linear crosstalk is proposed and experimentally validated. The proposed orthogonal multiplexing requires a precise Sinc-function spectral shape (square temporal shapes) which can be obtained by SSFBG technology. The orthogonal multiplexing is theoretically estimated to provide maximum spectral efficiency of 1 bit/s/Hz and the feasibility is demonstrated.

Acknowledgments

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