Systems performance comparison of three all-optical generation schemes for quasi-Nyquist-WDM

Arthur James Lowery,* Yiwei Xie, and Chen Zhu
Electro-Photonics Laboratory, Department of Electrical and Computer Systems Engineering, Monash University, Clayton, VIC 3800, Australia
*arthur.lowery@monash.edu

Abstract: Orthogonal time division multiplexing (OrthTDM) interleaves sinc-shaped pulses to form a high baud-rate signal, with a rectangular spectrum suitable for multiplexing into a Nyquist WDM (N-WDM)-like signal. The problem with generating sinc-shaped pulses is that they theoretically have infinite durations, and even if time bounded for practical implementation, they still require a filter with a long impulse response, hence a large physical size. Previously a method of creating chirped-orthogonal frequency division multiplexing (OFDM) pulses with a chirped arrayed waveguide (AWG) filter, then converting them into interleaved quasi-sinc pulses using dispersive fiber (DF), has been proposed. This produces a signal with a wider spectrum than the equivalent N-WDM signal. We show that a modification to the scheme enables the spectral extent to be reduced for the same data rate. We then analyse the key factors in designing an OrthTDM transmitter, and relate these to the performance of a N-WDM system. We show that the modified transmitter reduces the required guard band between the N-WDM channels. We also simulate a simpler scheme using an unchirped finite-impulse response filter of similar size, which directly creates truncated-sinc pulses without needing a DF. This gives better system performance than either chirped scheme.

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### 1. Introduction

“Orthogonal” time division multiplexing (OrthTDM) is based on interleaving $M$ modulated sinc pulses per TDM symbol. A practical application is to create a high-rate optical channel using lower-rate optical modulators [1]. The orthogonality is due to the peaks of one modulated pulse train aligning with the nulls of all other pulse trains. All of the pulses have the same spectral extent. The sinc pulse train of any one tributary, before modulation and multiplexing, is mathematically a superposition of delayed sinc pulses, with the delays being $M$-times the full width at half maximum (FWHM) of a single pulse’s peak. This signal is sometimes called “Periodic Sincs” (PSs) [2]. Practically, PSs can be created by spectral shaping of a high-rate short pulse source, such as a mode locked laser or an externally-modulated continuous-wave (CW) laser, to give $M$ equally spaced comb lines [2]. Alternatively a “Nyquist laser” [3] can be created by incorporating the spectral shaping within a mode-locked laser cavity. If $M$ is high enough, then the tails of the sinc pulses are much longer than the width of the central pulse, so approximate to infinite-extent sinc pulses. Thus, the spectrum of many pulses will be rectangular, and so can be used for dense wavelength division multiplexing – known as Nyquist WDM (N-WDM) [4].

Recently, Cincotti proposed [5] then experimentally verified [6] a method of generating an OrthTDM signal using a fractional Fourier transform (FrFT), implemented with an arrayed waveguide grating (AWG) router (AWGR) with a quadratic phase shift added to its paths, followed by a dispersive fiber (DF). The structure of the system is shown in Fig. 1(a). A FrFT is equivalent to a standard Fourier transform (FT) followed by a chirper. An inverse FrFT can create *chirped* orthogonal frequency division multiplexing (OFDM) symbols [5] from modulated input pulses. In chirped OFDM, each subcarrier undergoes a linear change of frequency with time, during each OFDM symbol. Conveniently, the chirping is a purely passive operation; that is, it does not require a phase modulator as used in many time-lens systems [7]. The chirped pulses can be compressed within a DF, so that each OFDM subcarrier within each OFDM symbol will be translated into a quasi-sinc pulse with a central-peak width equal to the inverse of the chirped spectral width. Because each OFDM subcarrier has a different frequency, they will also undergo different group delays in the fiber, so the peaks of the quasi-sincs will be offset from one another, allowing time-multiplexing, that is, OrthTDM. Finally, the OrthTDM can be wavelength multiplexed to be approximated to a N-WDM system (hence our use of quasi N-WDM).

An issue with such a scheme is that the quasi-sincs in a given symbol must have different central frequencies, in order that each receives a different delay in the DF. For example, as each has a near-rectangular spectrum due to chirping, a combination of inputs produces a convolution of these spectra with a comb of lines corresponding to the central frequencies of the subcarriers. The overall spectrum is broadened and has a triangular top, illustrated in Fig. [Fig. 1(a)](#241699)

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1(a). As we will show, this broadened spectrum will reduce spectral efficiency when multiple channels are wavelength multiplexed, because significant guard bands will be required between the N-WDM channels to reduce crosstalk.

In this paper, we first propose a modification to Cincotti’s scheme to increase its spectral efficiency, as shown in Fig. 1(b). The chirped FrFT is replaced by a chirped finite-impulse response (FIR) filter [8]. The chirped FIR filter could also be based on an AWGR, but with only one input. This filter is fed with optically-time division multiplexed (OTDM) pulses created by splitting, modulating, delaying then combining pulses from a mode-locked laser. Importantly, in our modified scheme, each of the interleaved pulses at the output of the DF will have the same spectrum, resulting in a narrower overall spectrum, so greater spectral efficiency in WDM systems. Interestingly, we will show this spectrum can be predicted by Fresnel diffraction theory.

We also consider a direct implementation of a near-Nyquist WDM filter, using an unchirped FIR with amplitude weighting of each of its waveguides to give a truncated-sinc (TS) impulse response, as shown in Fig. 1(c). No fiber is used, and as Fig. 1(b), the filter is fed with OTDM pulses. In our WDM system simulations, this simpler scheme outperforms the fiber-based methods because of its narrower spectrum, even though the TS pulses are shorter in duration. It should be noted that the removal of the chirping removes some of the processing flexibility available with chirped pulses, such as optical format conversion away from the transmitter [9].

The paper is organized as follows. Section 2 describes the modifications to Cincotti’s method. Section 3 provides an analytical expression for the modified method and identifies the key design parameter – the shape factor, \( S \). Section 4 develops the design rules for the filter and fiber. Section 5 compares the modified chirped FIR filter (Fig. 1(b)) with Cincotti’s design in systems simulations and demonstrates the importance of the shape factor for channel packing in WDM systems using the modified transmitter. Section 6 presents the design of an unchirped FIR filter (Fig. 1(c)), and compares its performance with the DF-based transmitters. The conclusion is drawn in Section 7.

2. Generation scheme for OrthTDM signals

Figure 2 illustrates the scheme presented by Cincotti [5], drawn as an AWGR with the signal processing equivalent below. The AWGR has \( M \) inputs (each labelled \( m \)), each fed with modulated pulses representing the data on a given subcarrier. The \( N \) outputs (each labelled \( n \)) of the first coupler feed the arrayed waveguides. The first slab coupler is configured as a Rowland circle [10], in which the phase shifts across it depend on the product \( m \times n \). This implements the phase weighing of the discrete inverse Fourier transform. The outputs, \( n \), are
each a sum of the phase-weighted inputs, \( m \). The arrayed waveguides and second slab coupler form a parallel-to-serial converter, because each waveguide provides an incremental delay over its neighbor [11]. Thus, if a pulse is fed into one of the inputs of the first slab, it will be split, and the resulting pulses will arrive almost simultaneously at the output side of the first slab. The differential lengths of the arrayed grating waveguides rearrange these pulses in sequence at the output of the second slab coupler. The chirping is achieved by adding a different phase shift to each path from the output side of the first coupler to the final output. This can be achieved by modifying the radius of the second slab coupler [5], or by adjusting the lengths of the arrayed grating waveguides themselves [8]. Importantly, the path losses from any input \( m \) to the final output should all be equal; otherwise the impulse response of the system will be apodized, leading to a spectrum with a curved top, and imperfect sinc pulses at the output of the DF.

An issue with this design is that the phase shift across the first slab coupler is also dependent on which input port \( m \) is being used; different inputs correspond to different central frequencies of the subcarriers. These frequency offsets must be designed to give the required time delays in the DF for each quasi-sinc pulse tributary, to achieve the time interleaving in OrthTDM. As each input produces a near rectangular spectrum, each rectangular spectrum will be offset, producing a triangular spectrum as shown in Fig. 1(a).

### 2.1 Modified design

If only a single input is used in Cincotti’s system, it will produce a train of widely spaced quasi-sinc pulses. Thus, it would be possible to devise a system using \( M \) copies of Cincotti’s system (with the same \( m \)), then combine their outputs to perform the orthogonal time-multiplexing of the quasi-sinc pulses. This would produce a spectrum as in Fig. 1(b). Unfortunately, this scheme would be wasteful of chip area. The AWGR would, however, reduce in functionality from being a fractional FT with a parallel-to-serial converter, to being a simple FIR filter with quadratic phase coefficients across the guides. Appropriate delays would need to be added to interleave the quasi-sinc pulses during multiplexing.

Because the FIR and following DF are both linear devices, a simplification is possible. This involves inputting OTDM tributaries to the single-input FIR filter. Because it is linear,
the output of the filter-DF combination will be a superposition of independently processed input pulses. Such a scheme is shown in Fig. 3.

![Diagram of filter-DF combination](image)

**Fig. 3.** Alternative scheme for generating Orth TDM, but with a narrower output spectrum than that of Fig. 2. The AWGR is fed with optically time-division multiplexed signal pulses. Mod is a modulator, typically a complex (I,Q) modulator for QPSK and QAM.

Starting with the signal processing block diagram (bottom of Fig. 3), the mode-locked laser produces very short pulses. This signal is split into $M$ paths, each of which is modulated and differentially time delayed, then recombined to produce a signal at $M$-times the mode-locked laser’s pulse rate. This is standard OTDM [12]. A chirped FIR filter is then used, which can be similar to the previous design, but with a single input. Thus, because the first slab need not act as a Fourier transform, it could be replaced by any power splitting arrangement; it would be advantageous to use power splitting/combining trees made from balanced $1 \times 2$ couplers, for example, as they may have less loss. The waveforms throughout the system of Fig. 3 are illustrated in Fig. 4, where a single input pulse from the mode-locked laser is transformed into a quasi-sinc pulse by filtering then compression in the DF fiber.

![Diagram of FIR filter](image)

**Fig. 4.** Generation of one quasi-sinc pulse using a chirped finite-impulse response (FIR) filter followed by a DF. The output of the FIR is the convolution (*) of the MLL pulse with the impulse response of the filter. Because the FIR imposes a frequency chirp upon the MLL pulse, the DF can compress the pulse.

The device’s operation relies on the processing being linear. This means that the modulated OTDM pulses input to the filter-fiber can overlap during processing without affecting one another.
3. Relationship to Fresnel diffraction

The phase and amplitude of the optical field of a chirped rectangular pulse is analogous to the field across a 2-D aperture with a point source some distance behind it. The FT of the chirped pulse (that is, its spectrum) is thus analogous to the far field away from the aperture, which is well known from Fresnel diffraction theory [13]. The spectral response of the FIR filter is therefore:

\[
F(f) = \frac{1}{\sqrt{4C}} \exp \left( -j \left( \frac{\pi}{4} + \frac{\pi(f_A - f)}{C} \right) \right) \times \exp \left( \text{erf} \left( \sqrt{\frac{\pi}{2C}} \frac{f_B - f}{2} + j \sqrt{\frac{2\pi}{C}} \frac{f_B}{2} \right) - \text{erf} \left( \sqrt{\frac{2\pi}{C}} \frac{f_A - f}{2} + j \sqrt{\frac{2\pi}{C}} \frac{f_A}{2} \right) \right)
\]

(1)

where: \(C\) is the chirp rate, \(f_A\) and \(f_B\) are the maximum and minimum instantaneous frequencies and \(\text{erf}\) is the error function. For example, if the chirp occurs over a time \(T_{\text{chirp}}\), then \(C = (f_B - f_A)/T_{\text{chirp}}\). In a similar manner to the diffracted far field from an aperture, the spectrum of a chirped pulse has stop-band leakage and pass-band ripples [13]. The normalized shape of the spectrum is solely determined by the dimensionless product, which we call the shape factor, \(S = T_{\text{chirp}}(f_B - f_A)\).

Figure 5 plots the FIR’s spectral response for two shape factors from Eq. (1) (thin solid lines) and from a MATLAB simulation of the spectrum of a chirped waveform (thick dashed lines). For a given shape factor, the traces overlap, which implies identical results, thus all traces appear to be dashed. For a given bandwidth \(B = (f_B - f_A)\), if \(S\) is increased (by increasing \(T_{\text{chirp}}\)), the ripple in the pass band is reduced, and the spectrum’s shape becomes closer to rectangular. This is equivalent to the far field from an aperture becoming more uniform as the aperture size is increased compared to the distance between the point source and the aperture. Numerical integration shows that almost 95% of the spectral energy is contained in the bandwidth \(B\) for \(S > 10\), when \(S = 100\), approximately 98% of the energy is confined between \(f_B\) and \(f_A\) [14]. From Fig. 5, it is clear that increasing \(S\) would reduce the crosstalk between adjacent WDM channels.

![Fig. 5. Effect of the shape factor, \(S\), on the FIR filter’s spectrum when the bandwidth \(B = 160\) GHz. The solid lines are from Eq. (1). The thick magenta/cyan dashed lines are from a MATLAB calculation of the FT of a chirped rectangular pulse.](image-url)
4. Design rules

The design of the FIR filter and the fiber is primarily determined by the required (FWHM) width, $\Delta T$, of the quasi-sinc pulses forming the OrthTDM channel, and their total duration including their tails. The ratio of their duration to their width determines how closely the pulses represent perfect (infinite duration) sinc pulses. The multiplexing ratio, $M$, determines the number of tributaries in OrthTDM, that is, how many quasi-sincs are interleaved in one period of the mode locked laser ($T_{\text{MLL}}$), giving

$$M = \frac{T_{\text{MLL}}}{\Delta T}. \quad (2)$$

4.1 Design of the FIR filter

To obtain a quasi-sinc pulse with FWHM of $\Delta T$ requires that the spectrum into the DF has a chirp bandwidth, $B$, which is equal to $1/\Delta T$, in the case of a large $S$. The chirping is implemented with a FIR filter with $N$ waveguides and phase weights across the filter. The free-spectral range (FSR) of the filter is the inverse of the incremental delay between the waveguides, $\Delta t$. At a minimum, the FSR could be just $B$, but this would cause difficulties in isolating one free-spectral range from the neighbors using a conventional band-pass filter (BPF) or wavelength multiplexer, so we shall make the $FSR = kB$, where $k$ is a scaling factor. Thus,

$$FSR = \frac{1}{\Delta M} = kB = \frac{k}{\Delta T} \quad (3)$$

The duration of the impulse response of the filter, $(N-1)\Delta t$, is equal to the duration of the chirped pulse, $T_{\text{chirp}}$, which should be chosen to be an integer multiple of $\Delta t$, so the number of guides is also an integer:

$$N = 1 + \frac{T_{\text{chirp}}}{\Delta M} = 1 + k\frac{T_{\text{chirp}}}{\Delta T}. \quad (4)$$

The relative phase shifts of the arrayed waveguides (which should include the phase shifts across the splitters), $\theta_i$ ($i = 0$ to $N-1$), can be found by calculating the phase shift at one extreme of the FIR response required to create a frequency shift of $B/2$, and by noting that a quadratic phase shift is required to impart a linear chirp. For an even number of guides, this gives the phase shift that should be applied by waveguide $i$, as

$$\theta_i = K\left(i - \frac{N+1}{2}\right)^2 \quad (5)$$

where $K$ is a factor related to the strength of the chirp and defined by

$$K = C\pi\left(\frac{T_{\text{chirp}}}{N}\right)^2 \quad (6)$$

where $\Delta t$ is the incremental delay of the waveguide delays, which should include the delays of the splitters. For example, a chirp of 160 GHz over a duration $T_{\text{chirp}} = 62.5$ ps ($C = 2.56 \times 10^{21}$ Hz/s, $S = 10$) with $N = 128$ waveguides, leads to $\Delta t = 0.49$ ps and $K = 0.00192$. Thus the phase shifts of the first and the last waveguides are 7.74 radians relative to the 64th or 65th waveguides.

4.2 Practical limitations to the duration of $T_{\text{chirp}}$

The duration of $T_{\text{chirp}}$ is practically limited by the physical size of the FIR filter; for example, if implemented as a waveguide array, a long $T_{\text{chirp}}$ implies significant waveguide losses in the longest waveguides. As a result, the output spectrum will have a sloping top. Nevertheless,
the problem can be solved by adding an attenuator in each arm of the FIR filter to equalize the losses. Another way to compensate the sloping top is to amplitude modulate the output of the FIR filter [15]. Alternatively, the FIR could be implemented with a chirped fiber Bragg grating (FBG) [16] and a circulator.

Another limitation is the periodic nature of the FIR’s spectral response, which repeats every FSR; a long $T_{\text{chirp}}$ results in a narrow FSR unless a large number of waveguides, $N$, is used. Practically, it is difficult to design AWG’s with more than 128 guides.

4.3 Choice of fiber

The dispersion of the fiber has to be chosen to compress the chirped pulses into quasi-sinc pulses. This can be thought of as delaying the leading edge of the pulse by $T_{\text{chirp}}/2$, and advancing the trailing edge by $T_{\text{chirp}}^2/2$, so they coincide (Fig. 4). Causality requires that a sufficient additional delay is added to ensure that all delays are positive. This is adequately provided by the propagation delay of the fiber. Because of the chirp (assumed positive here, to suit a standard telecoms fiber), the leading edge will have an instantaneous frequency $-B/2$, and the trailing edge $+B/2$. As the group delay of the fiber is:

$$T_{\text{group}} = D.L.\Delta \lambda$$

then the fiber’s dispersion parameter, $D$, multiplied by its length, $L$, must obey

$$D.L = \frac{T_{\text{chirp}}.\Delta f_s^2}{c}$$

where $f_0$ is the center frequency of the optical carrier and $c$ is the speed of light. As an example, for $T_{\text{chirp}} = 62.5$ ps, at 193.1 THz, a standard single-mode fiber ($D = 16$ ps/nm/km) would need to be 3-km long. This length could be reduced by using dispersion-shifted fiber (DSF), noting that the opposite sign of chirp would be required.

5. Systems simulations of the fiber-based transmitters

A system as in Fig. 6 generating 160-Gbaud signal per wavelength channel was simulated using VPItransmissionMaker, with a simulation bandwidth of 2.5 THz. The MLL produces 500-fs Gaussian pulses at 100-ps intervals. The MLL’s output was split into three paths; each is a wavelength channel in the N-WDM system. Each OTDM transmitter has 16 tributaries (to illustrate that low-bandwidth modulators can be used). Each tributary is modulated with QPSK or 16-QAM at 10 Gbaud using a complex optical modulator, delayed appropriately, and combined into an OTDM signal. Each FIR filter is tuned to produce a quasi N-WDM wavelength channel, with a nominal bandwidth, $B$, of 160 GHz and $T_{\text{chirp}} = 62.5$ ps. The shape factor, $S$, is 10. The FIR filters have 128 arms with differential delays of 0.49 ps, giving a FSR of 2 THz. Each N-WDM channel has a 240-GHz Gaussian 1st-order filter (BPF1) to remove energy from the higher-order passbands of the FIR filter. The N-WDM channels were then combined and fed through a common DF. This is the output of the N-WDM transmitter. Note that the multiplexing band-pass filters have overlapping pass bands in this design, but this is irrelevant as the FIR filters perform the fine spectral control.

The receiver used a second band-pass filter (BPF2), but with a bandwidth of 160 GHz, and a 2nd-order Gaussian response. The optical signal to noise ratio (OSNR) is defined as the average optical signal power in one channel divided by the power of the unpolarized amplified spontaneous emission (ASE) within a reference optical bandwidth (12.5 GHz). After the coherent receiver, we used least mean square (LMS) algorithms to recover the signal. The Q-factor is a performance metric, and was calculated from the means and standard deviations of the real and imaginary parts of the constellation points at the optimum sample times [17].

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5.1 Signal quality in single-channel and three-channel WDM systems

Figure 7 compares the signal quality versus OSNR for a single wavelength channel to that of the central channel in a 3-channel N-WDM system with no frequency guard bands (i.e., a 160-GHz WDM channel spacing). We chose $N$ as 128 and 256 to simulate $S = 10$ and $S = 40$, respectively; if $N = 128$ had been used for $S = 40$ then the FSR would have been too narrow. The 16-QAM signals have larger penalties, because higher-order modulation formats are more sensitive to inter-symbol interference (ISI). The WDM systems have much larger reductions in signal quality than the single-channel systems, due to crosstalk from neighboring channels. The $S = 40$ case (red) always gives better performance than for $S = 10$ (black); this because the crosstalk between the WDM channels is reduced when $S$ is increased, as described in Section 3. The largest reduction in signal quality is for a WDM system using Cincotti’s design (green line) due to the wide spectra of each channel. This system would have error rates in excess of the 7% FEC limit for QPSK, whereas the modified WDM system would support QPSK without a guard-band.

5.2 Required shape factor for a given signal quality and guard band

In practical N-WDM systems, a guard band is introduced between the channels to reduce inter-channel crosstalk. This means that the channel spacing is made wider than the nominal channel bandwidth, $B$. We define the guard band ratio as the guard-band’s bandwidth divided...
by $B$. In the following simulations, we find the required shape factor, $S$, to give a signal quality of 8.52 dB for QPSK and 15.2 dB for 16-QAM (both equivalent to a BER of $3.8 \times 10^{-3}$), for a range of guard-band ratios. We used OSNRs of 18 dB for QPSK and 32 dB for 16-QAM. In the single-channel case, 16-QAM should require only 6.7 dB better OSNR than QPSK; however, as Fig. 7 shows, the crosstalk in the N-WDM case severely limits the signal quality.

Figure 8 depicts the minimum guard band ratio for different $S$ when the central channel is demultiplexed using a 160-GHz 2nd-order Gaussian filter. When $S = 5$, the required guard band ratio has to be greater than 27% for QPSK and 30% for 16-QAM. For $S = 80$, the guard band ratio only needs to be >0.2% for QPSK and 0.5% for 16-QAM. However, such a large shape factor requires a physically large FIR filter and a longer fiber. Thus, adding a guard band is a necessary compromise, although it will proportionally impact the spectral efficiency.

6. Direct truncated-sinc pulse generation using a FIR filter and no DF

6.1 Design of the unchirped FIR filter

An open question is whether the systems using a chirped filter plus a dispersive filter would perform as well as a more direct approach such as using a filter with a TS impulse response with no fiber after it; Fig. 9 shows this approach. In this example, the duration of this TS pulses equals the MLL pulse spacing. This would require a filter with a similar physical size to the $S = 10$ case in Fig. 3 ($N = 128$). Neglecting power conservation for simplicity, the TS impulse response is defined as

$$h(t) = \sin c \left( \frac{t-T_{\text{MLL}}/2}{\Delta T} \right) \cdot \text{rect}_{T_{\text{MLL}}/2} \left( t - \frac{T_{\text{MLL}}}{2} \right)$$

(9)

where the rectangular function used here is: $\text{rect}_{T_{\text{MLL}}}(t) = \begin{cases} 1 & \text{if } 0 \leq t \leq T_{\text{MLL}} \\ 0 & \text{otherwise} \end{cases}$. 

Fig. 8. Required shape factor to support QPSK and 16-QAM versus guard band ratio.
The FIR’s input splitter uses a binary tree of power splitters. To generate a sinc pulse with width of $\Delta T = T_{\text{MLL}}/M$, the power split ratio of each arm of the FIR filter can be calculated as:

$$
\gamma_{\text{out},i} = \frac{1}{A} \sin c \left( \frac{(i-1) \Delta T - T_{\text{MLL}}/2}{\Delta T} \right)^2, \quad 1 \leq i \leq N
$$

where $A = \sum_{i=1}^{N} \sin c \left( (i-1) \Delta T - T_{\text{MLL}}/2 / \Delta T \right)^2$.

The phase response of a truncated-sinc pulse can be realized by the phase added after the waveguides, which themselves form a parallel-to-serial converter. Finally, the spectral response of the FIR is simply the spectrum of a sinc pulse convolved with the spectrum of the rectangular window defining the truncation of the sinc. Just as with the chirped pulse spectrum, this spectrum is similar to a physical optics situation of the far field of an aperture illuminated by a distant point source; that is, Fraunhofer diffraction [13].

### 6.2 Simulation comparison of all three systems in Fig. 1

A system as in Fig. 6 generating 160-Gbaud signal per wavelength channel using an unchirped FIR filter was simulated using VPItransmissionMaker. Each FIR filter has 128 arms with differential delays of $T_{\text{MLL}}/128$, giving a FSR of 1.28 THz. In single channel system, we used BPF1 to remove energy from the higher-order passbands of the FIR filter.

Figure 10 compares the sinc pulse generated by three schemes and signal quality versus OSNR in single-channel systems. As shown in Fig. 10(a), the chirp-free TS impulse response that is generated by the unchirped FIR scheme matches well to the ideal sinc pulse. Although the chirped AWG and chirped FIR schemes give different shaped spectra, as shown in the inset of Fig. 10, they have similar chirped impulse responses, all of which are slightly different to the ideal sinc response. There are small offsets in the position of their nulls, as shown in the inset of Fig. 10(a). This produces a 0.4-dB reduction in signal quality for a given OSNR, as shown in Fig. 10(b). The time bandwidth products are: 1.0625, 1.6875 and 2 for truncated-sinc direct FIR filter generation, quasi-sinc chirped-FIR and Cincotti’s chirped-AWG method, respectively ($S = 10$). The time bandwidth product is defined as $\Delta T \times B_w$ (between $-20$ dB points).
Fig. 10. (a) Comparison of the quasi-sinc pulse generated by a chirped FIR and Cincotti’s chirped AWGR with a DF (VPItransmissionMaker simulation with $S = 10$, $T_{ML} = 100$ ps, $\Delta T = 6.25$ ps), truncated-sinc pulse generated by a truncated-sinc FIR (VPItransmissionMaker) and ideal sinc pulse simulated in MATLAB. (b) Comparison of the $Q$ factors for QPSK systems using the three different transmitters in single-channel systems.

The performances of these three different schemes with 3-channel N-WDM systems (160-GHz spacing) are shown in Fig. 11(a). The proposed unchirped FIR filter system suffers some inter-channel interference (ICI) from adjacent channels due to its limited shape factor; however, the OSNR penalty is less than the modified chirped FIR filter in Fig. 1(b) and much less than for Cincotti’s scheme in Fig. 1(a). Obviously spectral guard bands can be introduced to improve the performance of the WDM systems. As shown in Fig. 11(b), the $Q$ factor saturates when guard band ratio reaches 6.25%, which indicates that a 10-GHz guard band is required to obtain the same performance as in a single channel system. For the modified chirped FIR and direct FIR systems, the ICI is negligible when the guard band ratio is large; the signal quality is now limited by the receiver filter. At the receiver, we used a BPF2 to select the central channel from the WDM signals. The occupied bandwidth (−20 dB points) of the modified chirped FIR ($S = 10$) is 270 GHz, for the modified chirped FIR ($S = 40$) is 230 GHz, and for the direct FIR is 170 GHz. The spectrum of the central channel is narrowed due to this filter, thus the $Q$-factor of central channel is lower for the chirped FIR system than that for a single-channel system.

Fig. 11. (a) Comparison of the $Q$ factors for QPSK systems using three different transmitters. (b) The $Q$ factors for three WDM channels with respect to guard band ratio using truncated-sinc FIR of Fig. 1c, chirped FIR of Fig. 1b and unmodified chirped systems of Fig. 1a (OSNR = 20 dB).

7. Conclusions

In this paper, we have shown that a simple modification to Cincotti’s method of OrthTDM pulses reduces the spectral width of each quasi N-WDM channel. We then showed that a channel’s spectrum can be predicted using Fresnel diffraction theory. This analogy identifies an important system design parameter, the shape factor, $S$, which should be made large for
well-controlled spectra that have flat tops and fast transitions to their stop bands. We have also shown the effect of crosstalk in N-WDM systems on signal quality, and shown that there is a trade-off of shape factor against guard band width for a given OSNR. Unfortunately, a large shape factor requires a finite impulse filter with a long duration. This filter, therefore, has to be physically large, and has to have many waveguides to support a suitable free-spectral range.

A third approach is to design a filter which directly gives truncated-sinc pulses, so removes the need for a dispersive fiber. This has a spectrum that is the convolution of a narrow sinc and a wider rectangular spectrum, which is generally narrower than using the chirped techniques, above. This approach gives the best WDM system performance of all-three designs. It does, however, remove some of the possibilities for post-processing the pulses after transmission, as they are no longer chirped.

Finally, there will always be a residual crosstalk penalty for these systems, when compared with OFDM systems. This is because the channels cannot be demultiplexed orthogonally, as there is no synchronization between the transitions of the modulated symbols of each tributary [18].

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