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Photonic Circuit Topologies for Optical OFDM and Nyquist WDM

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***Abstract*—: Photonic circuits are the key to advanced functionality in future optical systems, as they efficiently process terabit/s data streams. This paper reviews how photonic circuit topologies have evolved to support high-spectral efficiency modulation formats, including: All-Optical Optical Frequency Division Multiplexing (AO-OFDM), Discrete Fourier Transform Spread OFDM (DFT-S-OFDM), Nyquist Wavelength Division Multiplexing, (NWDM), Orthogonal Time Division Multiplexing (OrthTDM, OTDM), chirped-OFDM and quasi-Nyquist signals. The importance of the order of components such as modulators, delays and filters within these circuits is stressed, as simple changes to the circuit topology have significant impacts on the spectra of the signals, and the required bandwidths of the modulators.**

***Index Terms*—Optical OFDM, Nyquist WDM, Coherent Optical OFDM, Optical Signal Processing, All-Optical, Optical Fourier Transform, Arrayed Waveguide Grating Router, Cyclic Prefix, Photonic Integrated Circuit**

I. Introduction

OPTICAL OFDM [1] [2] [3] and Nyquist WDM [4] both support high spectral efficiencies by either allowing: subcarriers to overlap (O-OFDM), or by tightly controlling the spectral extent of each wavelength channel (N-WDM). Electronic generation of these signals can provide flexibility, but at a significant energy cost for the high-speed digital-to-analog converters [5]. Electronic demultiplexing requires oversampling to select a particular channel from its neighbors, and is usually combined with optical demultiplexers as a first stage [6]. That said, many functions that were traditionally performed optically, such as dispersion compensation, are now performed by digital signal processing (DSP) of coherently detected signals. An advantage is that DSP enables a simplified outside-plant design with no inline dispersion compensators [7-9]. DSP can also provide some compensation of fiber nonlinearity (NL) [10].

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An ideal world is where the processing is shared between optical and electronic methods, and this sharing is dynamic, to minimize energy consumption. The goal of the Electro-Photonics Laboratory at Monash University is to develop such methods and we have assembled a team with experience encompassing photonic and electronic circuit design methods to achieve this goal.

This paper reviews the work of our team and of other teams across the world. Although the initial aim of our work was to build all-optical OFDM systems with electronic processing where necessary; however, hybrid signal formats, spanning OFDM to its 'dual' N-WDM could offer the best of all worlds [11].

This work is an extension of an invited paper, presented at OFC 2016 [12]. Section II introduces the general concept of multiplexing orthogonal sub-channels and the role that photonic chips can play in such systems. Section III covers the generation and reception of Optical OFDM signals, then presents photonic chip implementations of O-OFDM based on optical Fourier transforms. Section IV covers the generation and reception of N-WDM signals. Section V discusses other related signal formats, such Discrete-Fourier-Transform-Spread Optical OFDM (DFT-S-OFDM) using periodic-sinc pulses, and signals generated by fractional Fourier transforms, such as chirped-OFDM and quasi-Nyquist signals and their related spectra. Section VI draws conclusions.

II. Sub-Channel Multiplexing

The aim of multiplexing is that the receiver can separate out the transmitted sub-channels (*subcarriers* in OFDM, and *wavelengths* in Nyquist WDM) with low mutual interference. In systems with a single-carrier per wavelength (such as Nyquist WDM), multiplexing is often implemented by band-limiting each transmitted sub-channel so it does not substantially overlap with neighboring sub-channels in the frequency domain. At the receiver, frequency-domain filtering can then be used to demultiplex the sub-channels.

In contrast, in OFDM the subcarriers spectrally overlap, but are designed so that they can be orthogonally demultiplexed—that is, with zero mutual interference. Although electronic OFDM systems typically use Fourier transforms for the orthogonal demultiplexing, as do some optical OFDM systems, in all-optical OFDM, banks of optical filters generally take the place of Fourier transforms. As we shall see, the Arrayed Grating Wavelength Router (AWGR) can also implement the inverse and forward Fourier transforms, for the generation and demultiplexing of optical OFDM signals.

For both NWDM and OFDM, the sub-channels must be orthogonal in order to be demultiplexed at the receiver side without interference from neighboring sub-channels. Mathematically, two received sub-channels (s_i and s_j) will meet the orthogonality criterion, which is that their cross-correlation, c_{ij}, including a weighting function $w(t)$ equals zero:

$$c_{ij}(k)=\int_{-\infty}^{\infty} s_i(t)\,s_j^*(t)\,w\left(t-\frac{k}{R}\right)dt \qquad (1)$$
$$c_{ij}\equiv 0 \text{ for } i\neq j$$

where: k is the index of the symbol, R is the symbol rate, t is time, and * indicates the complex conjugate. The weighting function, $w(t)$, is usually rectangular and has the duration, T, of a single symbol period. For NWDM, orthogonality is ensured by the frequency separation of s_i and s_j being greater than $1/T$ [4]. In OFDM, with overlapping sub-carriers, orthogonality relies on precise frequency separation [1-3].

Practically, the receiver needs to process each symbol k on each sub-channel n over interval T, to be able to extract the data symbol, $d_n(k)$, carried on each sub-channel, $s_n(t)$. This can be achieved for one sub-channel by applying an analysis function, $a_n(t)$ [13], *i.e.*:

$$d_n(k)=\int_{k/R}^{(k/R)+T} s_n(t)\,a_n\left(t-\frac{k}{R}\right)dt \qquad (2)$$

The analysis function is designed to reject all sub-channels except one. The function a_n can be viewed as a matched filter for the sub-channel, with sampling at the correct instance to recover data. Because of its similarity to convolution, Eq. (2) can be implemented by a bank of optical filters and samplers.

In this paper, we concentrate on implementing the optical filters and Fourier transforms within photonic integrated circuits, placed after transmitters or before receivers, as shown in Fig. 1. One aim is to simplify the receiver's DSP, to reduce power consumption. In the case of optical OFDM, the filters are designed with sinc-shaped spectra (which implies a rectangular-envelope impulse response in the time domain), while in Nyquist WDM, a rectangular spectrum is desired (which would require an infinite-duration sinc-envelope impulse response).

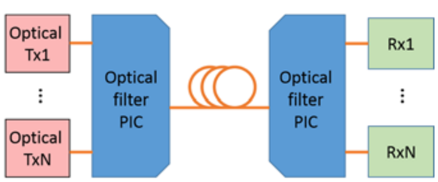

Fig 1. Basic schematic of photonic integrated circuit (PIC) assisted optical super-channel transmission. The filter PICs are generally designed to process multiple sub-channels simultaneously.

III. Optical OFDM

A. OFDM signals and spectra

Optical OFDM transmitters [14-16] deliberately overlap the spectra of the subcarriers, with the spectrum of each subcarrier being sinc-shaped. Unfortunately, this overlap makes it difficult to demultiplex a particular subcarrier without specially designed filters with overlapping responses, and thus can be an obstacle to wavelength routing. If the OFDM channel is generated electrically, tens to thousands of subcarriers can be used per wavelength [2, 17]. Thus, even though each subcarrier has significant spectral tails, compared with the subcarrier frequency spacing, these do not significantly broaden a wavelength channel composed of many subcarriers. If, however, the OFDM signal is generated all-optically [18, 19] (as is the focus in this paper), only a few subcarriers might be used per wavelength channel, and the spectral tails will be significant in bandwidth, so special filters (usually based on Fourier transforms) will be required. However, to mitigate this issue, optically generated subcarriers can be transmitted, routed and received in defined groups—optical super-channels [20, 21].

Optical OFDM transmits its subcarriers in 'blocks' or *OFDM symbols*, with their modulation being synchronized so that all the symbol transitions of all of the subcarriers align at the receiver [22]; the modulated amplitude and phase of each subcarrier also have to be constant throughout the symbols, as shown in the waveform in Fig. 2(left) for one subcarrier. The reason for this requirement is due to the receiver: if the phase or amplitude of a particular subcarrier is modulated *during* a symbol, this subcarrier will be broadened by this modulation and so will have spectral leakage into the adjacent subcarriers, causing inter-(sub)-carrier-interference (ICI). Because of this requirement of constant amplitude and phase over a symbol, the power spectral density of each subcarrier, measured over many symbols, has a sinc-squared shape.

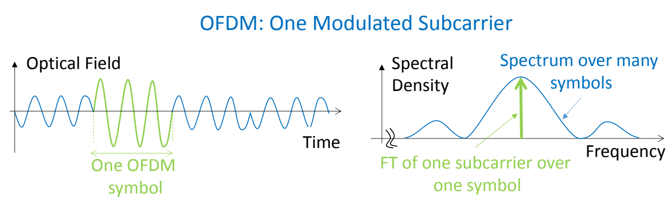

Fig. 2. Waveform and spectrum of one OFDM subcarrier. Note how, in this special case of a single subcarrier, the output of the Fourier Transform (FT) of one OFDM symbol is non-zero only at a single frequency.

The frequency spacing of the subcarriers is arranged so that they are all periodic (have integer numbers of cycles) within the receiver's window, $w(t)$. Thus, Eq. 1 is satisfied, and the subcarriers can be recovered without inter-(sub)-carrier-interference (ICI). This is illustrated in Fig. 2(right), where the spectrum of one (periodic) subcarrier, when analyzed over one OFDM symbol, is a delta function (green). Conveniently, a Fourier transform is equivalent to a bank of matched filters followed by samplers, so it can recover the amplitudes and phases of all of the subcarriers in one (electrical or optical) operation.

B. All-optical OFDM transmitters

As we are considering photonic-chip implementations of OFDM, it is natural to restrict the discussions to all-optical OFDM, where the subcarriers are each generated using individual electro-optic modulators, then combined optically. There are several approaches to this, described below.

1) CW lasers and fast modulators

This method [23], shown Fig. 3, requires very high bandwidth optoelectronic modulators, otherwise the amplitude and phase in each subcarrier will vary during a symbol, causing loss of orthogonality at the receiver, as was discussed above. The bandwidth of each modulator has to be several times the symbol rate of an individual subcarrier; indeed, it should exceed the combined bandwidth of all of the subcarriers. Thus, if we have a high-bandwidth modulator, a better use of it might be to generate all of the subcarriers; that is, not use multiple modulators or even all-optical OFDM. The lasers need not be frequency locked, but each has to be stable in phase over each OFDM symbol (i.e. have a narrow linewidth compared with the symbol rate) to avoid loss of orthogonality on reception.

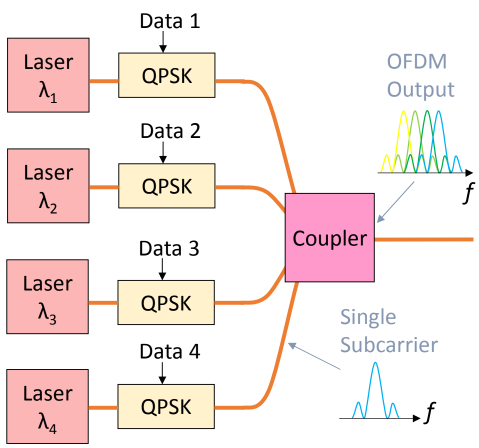

Fig. 3. Simplest form of all-optical OFDM transmitter using separate CW laser sources.

2) Demultiplexed spectral comb source

This method, shown in Fig. 4, uses an optical comb source to provide coherent carriers that are then demultiplexed for modulation by individual modulators [24]. The comb can be a mode-locked laser or a strongly-modulated CW laser. Using a single laser source has the advantage that the subcarriers are frequency locked, which enables ICI-free operation. Frequency locking also enables compensation of cross-phase modulation (XPM) caused by fiber nonlinearity [25]. Unfortunately, it also requires very high bandwidth optoelectronic modulators for the same reasons as above.

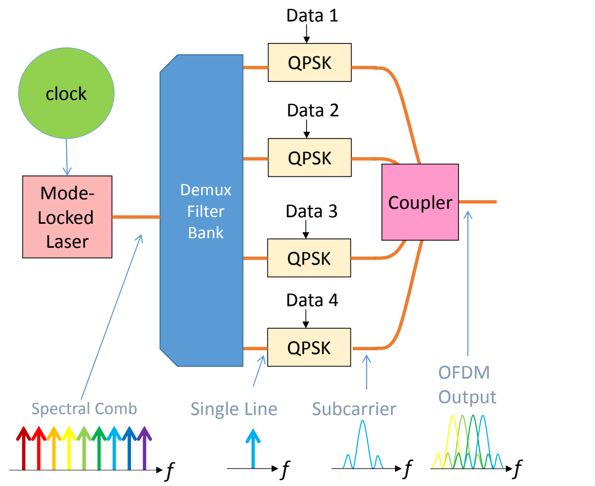

Fig. 4. All-optical OFDM transmitter using a mode-locked laser as a frequency comb source with a demultiplexing filter before the modulators.

3) Modulate pulses then pulse shape

This method, shown in Fig. 5, sends the pulses from the pulsed source laser directly to the modulators without demultiplexing them into separate frequency tones. This relaxes the need for high-bandwidth modulators, because each modulator need only be in the correct ‘state’ while a particular optical pulse passes through it [26, 27]. The modulation produces a nearly ‘white’ spectrum as it is at the same symbol rate as the pulse-repetition rate of the laser [28]. The actual width of the spectrum is approximately 0.44/(pulse width) for Gaussian-envelope pulses, so 2-ps pulses will produce a spectral width of 220 GHz. Note that modulation formats that have a baseband DC component (producing a strong carrier tone after modulation onto a lightwave) will have a comb spectrum superimposed upon the white spectrum. However, if modulation formats with a suppressed carrier are used, such as QPSK, the comb part of the spectrum will not be present.

To assign the modulated pulses to a particular wavelength channel, they can be spectrally shaped using an optical filter bank; each filter’s response should approximate to a rectangular-envelope ringing waveform, lasting the duration of an OFDM symbol. This technique has been demonstrated with Liquid Crystal on Silicon (LCoS) “wavelength selective switch” technology [29, 30], which has the benefit that many types of signal (N-WDM, OTDM, OFDM) can be ‘shaped’ from the same optical input pulses—producing a ‘universal transmitter’ [31]. Interestingly, as explained in [28], for signals without a DC component, each modulator’s output can be assigned to any wavelength within the ‘white’ spectrum, and not just discrete wavelengths on the original frequency grid of the comb source. A simple explanation is that each modulated pulse approximates to an impulse, and as impulses have a ‘white’ spectrum they can be spectrally shaped to become subcarriers with an optical filter centered upon any frequency. Furthermore, a single modulator’s output can be assigned to *multiple* wavelength channels, just by changing the filtering function to have multiple pass-bands. This is useful, for example, when creating test signals that must occupy the majority of the fiber’s bandwidth, or broadcasting a channel to receivers tuned to different wavelengths.

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Schröder *et al*. showed that a wavelength selective switch (WSS) can be used as a Fourier transform for the generation of optical OFDM signals that include a cyclic prefix [30]. This method simply requires the spacing of the central frequencies of the filters to be increased above the data-symbol modulation rate, while the bandwidth of each filter was kept as before. This offers the interesting possibility of optimising the duration of the cyclic prefix to suit the accumulated dispersion of the fiber plant, without wasting spectral efficiency with an overly long cyclic prefix.

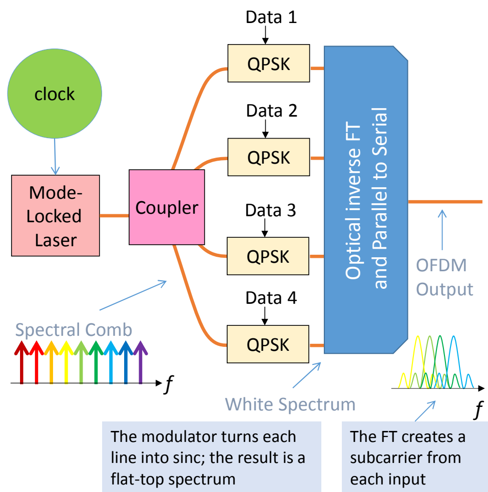

Fig. 5. All-optical OFDM transmitter using a mode-locked laser as a pulse source. The modulation turns each comb line into a sinc spectrum; in most cases, the sum of these spectra is a white spectrum.

C. *OFDM receiver topologies*

An OFDM receiver's processing can be achieved in the electrical domain, but with a bandwidth limited by the sample rates of the analog to digital converters (ADCs). Thus, for continuous (gap-less) super-channels with bandwidths exceeding the capabilities of ADCs, at least, optical processing is necessary.

To implement Eq. (2), a bank of optical filters with rectangular-envelope impulse responses is required. These produce 'eye diagrams' with only a narrow 'open' window, as shown in Fig. 6 [32, 33]. Thus sampling with a very short sampling window is required to capture the output of a subcarrier's filter only when there is no interference from other subcarriers. In the time domain, this instant corresponds to when the impulse response of the filter aligns with a single symbol in the OFDM waveform. Preferably the sampling is performed in the optical domain, otherwise, if performed in the electrical domain, the receiver will have to have a bandwidth of several times the symbol rate of an individual subcarrier. This is practical for low symbol rates (e.g. 12.5-GHz receivers for 5-Gbaud subcarriers [34] with a photonic integrated DFT). A high bandwidth receiver also enables the demultiplexing to be partially performed in the electrical domain, as used by Sano *et al*. in a 13.4 Tbit/s system [19].

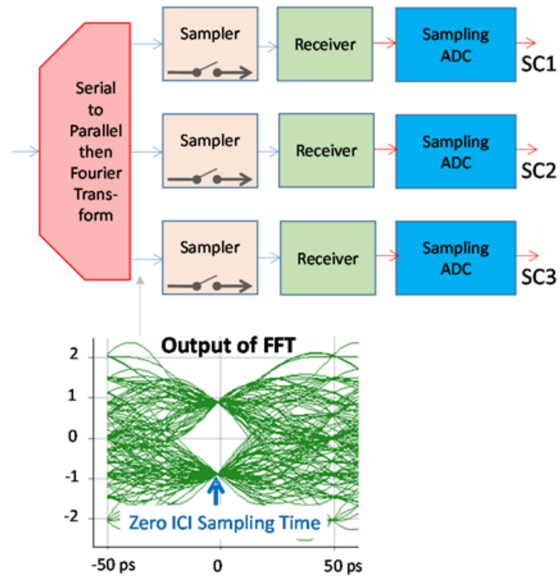

Fig. 6. All-optical OFDM receiver using a continuous Fourier transform (and implicit parallel to serial conversion), followed by optical samplers, receivers and finally ADCs that implicitly sample the outputs of the receivers.

There are several methods of implementing the filter bank, described below.

1) *Wavelength selective switches*

Du *et al*. have demonstrated the use of wavelength selective switches at both the transmitter and receiver to implement a 10-Tbit/s OFDM system [35], using 10-Gbaud subcarriers. The fast sampling after the demultiplexing filters was achieved using a wide-bandwidth coherent receiver and an 80-GS/s real-time oscilloscope.

2) *Coupler-based Fourier transforms*

Marhic developed Fourier transforms based on combinations of 2×2 optical couplers, delays and phase shifters in 1987 [36]. In 2002, Sanjoh, Yamada and Yoshikuni proposed a two-subcarrier optical OFDM receiver using delay lines, couplers and samplers [37]. In 2008, Lee, Thai and Rhee simulated a four-subbcarrier system using 4-output splitters [38], and also suggested that it might be possible to use an AWGR with additional delays and a coupler to implement a FT. Huang *et al*. have used unbalanced Mach-Zehnder interferometers as 2-point FTs at the transmitter and receiver of a dual-polarization OFDM system [39]. Takiguchi *et al.* demonstrated a planar waveguide eight-channel OFDM receiver using a serial-to-parallel converter (SP) followed by two 4-point FTs and a final stage to create an 8-point FT [40].

Hillerkuss *et al.* simplified Marhic's network to avoid cross-overs, as shown in Fig. 7 [41]. This network has implicit serial-to-parallel conversion, provided by the delays within the MZI stages. It has been used in demonstrations of all-optical OFDM systems with tens of Tbit/s capacity [20]. Because Marhic's arrangement of couplers looks similar to the 'butterfly' structure of the signal-processing of a digital fast Fourier transform (FFT) [42], these arrangements of splitters-couplers are often referred to as optical *fast* FTs (that is, FFTs).

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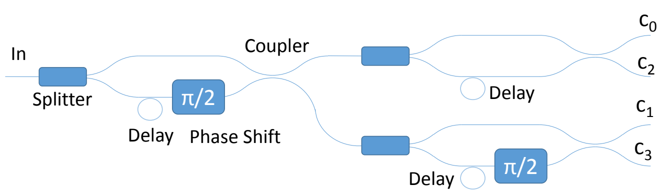

Fig. 7. All-optical 'fast' Fourier transform based on 2×2 couplers and 1×2 splitters, delays and phase shifts.

3) *AWGR as a Fourier Transform*

As shown in Fig. 8, the arrayed waveguide grating router (AWGR) comprises two 'free-space' coupling slabs connected together with an array of waveguides [43]. The slabs confine light vertically, but allow light coupled into one side (with waveguide tapers acting as antennas) to spread horizontally to the opposite side, to be collected by a second set of antennas. Because one antenna couples into many antennas at the other side of the slab, the slabs can act as couplers or splitters. The amount of spreading, hence the coupling ratios, is determined by the far-field beam patterns of the antennas. The slabs can be designed to give particular phase shifts across them that is dependent on the positions of the inputs and output waveguides (e.g. $\theta_{n,m}$). The arrayed waveguides are usually designed to give incremental delays, ΔT.

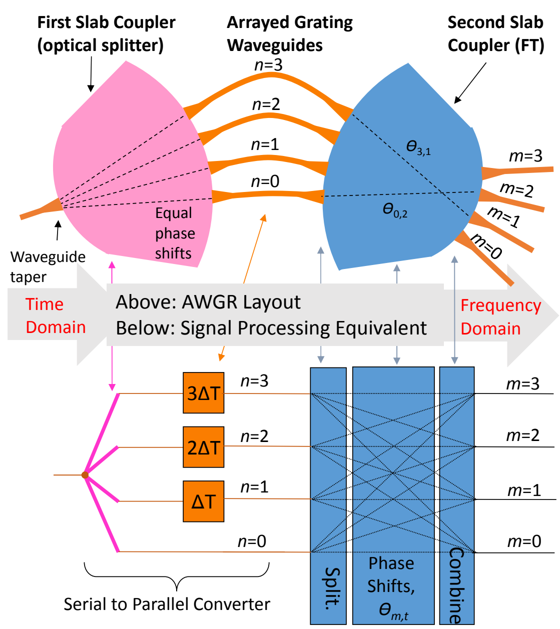

Fig. 8. AWGR design (top) and its signal processing equivalent (bottom) when acting as a forward FT.

The AWGR can be designed to approximate to a Fourier transform, preceded by a serial-to-parallel (SP) converter [32, 33, 44]. Cincotti *et al.* had earlier used AWGRs as coders/decoders in CDMA (Code Division Multiple Access) systems [45, 46], of which OFDM can be considered a subset of CDMA but with a 'frequency' code; that is, each data channel is assigned to a different frequency.

The slab-waveguide-slab structure of a typical AWGR is often considered to be 'just a FT', though the SP converter is critical to the operation of the system. The signal processing equivalent is shown in the bottom half of Fig. 8, and its blocks correspond to the AWGR in the top half of Fig. 8. The serial-to-parallel converter is formed by a 1-to-n slab coupler (pink) followed by the array of waveguides of incremental lengths (orange). This arrangement effectively 'copies' (with loss) the input signal and then applies different delays to the copies. Thus a continuous waveform at the input will output the waveguides as multiple, differentially delayed, copies. Therefore, at a given instant, the outputs of the waveguides that are presented to the second slab are consecutive samples of the input waveform. Thus, functionally, serial-to-parallel conversion is achieved.

The Fourier transform itself is performed by the second slab coupler (blue). This is arranged so that the phase shift from input waveguide n to output m is approximately proportional to the product $n \times m$. Thus a given output receives a phase-weighted sum of the delayed samples exiting the arrayed waveguides. This is equivalent to the discrete sum of phase-weighted samples in a Fourier transform.

Of course, to be a Fourier transform without any amplitude weighting (or windowing) of the input waveform, the path losses across the whole device, for a given value of m, must be identical for any value of n. This is generally not the case for an AWGR, because the input waveguides to a slab will couple to the output waveguides proportional to their far-field beam patterns. The beam can be expanded, to give a more-uniform illumination of the output waveguides. This provides a better approximation to a uniform window FT, but increases the average loss across the device as much of the 'beam' is not collected by the output waveguides.

To implement an AO-OFDM transmitter, an inverse FT is required. This is simply the forward FT with its inputs and outputs swapped. That is, the input slab acts as the inverse FT, with the waveguides and the second slab acting as a parallel-to-serial converter. Fig. 9 shows an AO-OFDM transmitter design including an extra slab coupler at the input (pink), which splits pulses from a mode-locked laser to a bank of modulators (mod), which then feed an FT (blue slab) followed by a parallel-serial converter (waveguides and right pink slab) to produce a time domain waveform. An additional waveguide (green) is used in the AWGR design to provide a cyclic extension to the output waveform [47]; in this case it is a cyclic *post*-fix as it has a greater delay then the original waveguides. The OFDM symbol rate (and data rate) should be decreased relative to the subcarrier spacing to accommodate the cyclic prefix. As shown in the simulated eye diagrams in Fig. 9, the CP broadens the width of the open part of the eye, so allows for less-accurate timing of the sampler, to accommodate clock timing jitter, for example.

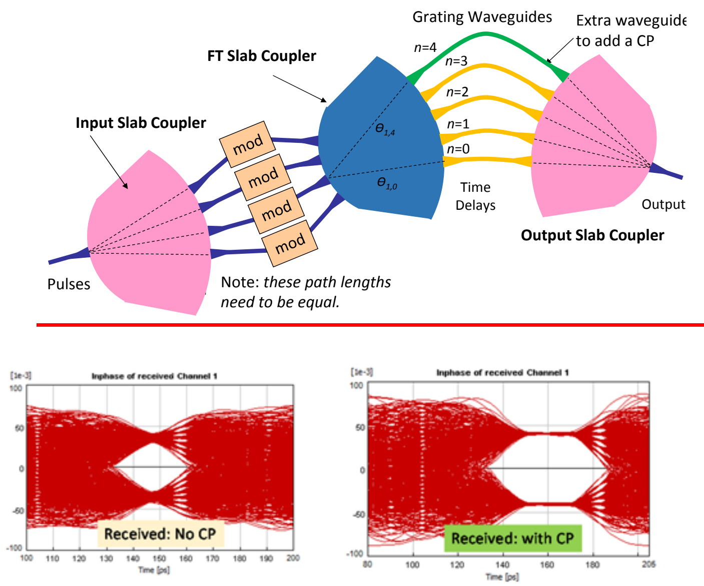

Fig. 9. All-optical OFDM transmitter using AWGR technologies, and received eye diagrams (after receiver FT) with and without the CP waveguide. The input and output slab couplers (pink) could each be replaced by alternative splitter/coupler technologies such as trees of 2×2 couplers or multi-mode interference couplers.

As shown in Fig. 10, the receiver's AWGR-based circuit is a mirror image of the transmitter circuit, except that the modulators are replaced by samplers, and the outputs of the samplers must be fed into individual photo-receivers, to give the topology of Fig. 6 [32]. If a CP has been added at the transmitter using an additional waveguide, the corresponding waveguide (or waveguides) at the receiver must be deleted from the AWGR. This means that the time sample(s) corresponding to the CP will be discarded at the receiver, as in conventional OFDM designs using digital signal processing to strip the CP before the FT. In effect, the duration of the weighting function, $w(t)$, in Eq. (1) is being defined by the delay difference between the shortest and longest waveguides.

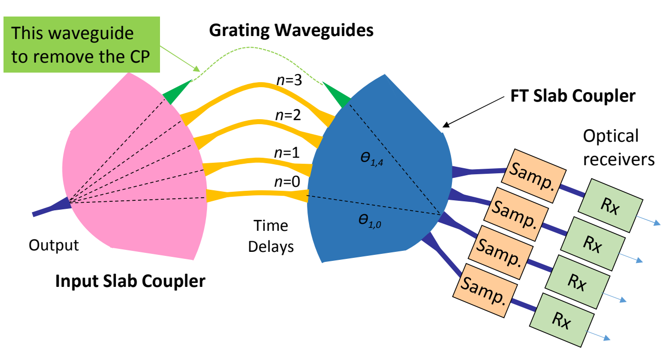

Fig. 10. All-optical OFDM receiver using AWGR technologies. The key component is the final slab coupler which acts as an $n\times m$ Fourier transform. The array of waveguides before this coupler, and the first slab coupler act as a parallel-to serial converter. The first slab coupler could be replaced by alternative splitter/coupler technologies such as trees of 2×2 couplers or multi-mode interference couplers.

D. Demonstrated photonic chips

Experimentally, AWGRs have been included into photonic chips and demonstrated in chips [48]. These usually replace the 'pink' slab coupler with a tree of 1×2 splitters to even out the waveguide powers.

Fig. 11 shows a design developed by Monash University and VLC-Photonics (Spain), which has been demonstrated as part of a system [49]. Active control of the waveguide phase shifts was not used. The bottom picture is a screen-shot of the layout before production. The top photomicrograph shows the input slab coupler, followed by a set of racetrack delays forming the parallel to serial converter. The outputs of the delays are combined by a tree of 2×1 couplers (only one set shown). The middle plot shows the wavelength response of each input. These are not ideal sinc responses, due to the uncertainties in manufacturing and also because of uneven path losses from the inputs to the outputs, partially due to the far-field patterns of the couplers that couple to the slab, and partially because of the larger optical losses of the longer racetrack delays.

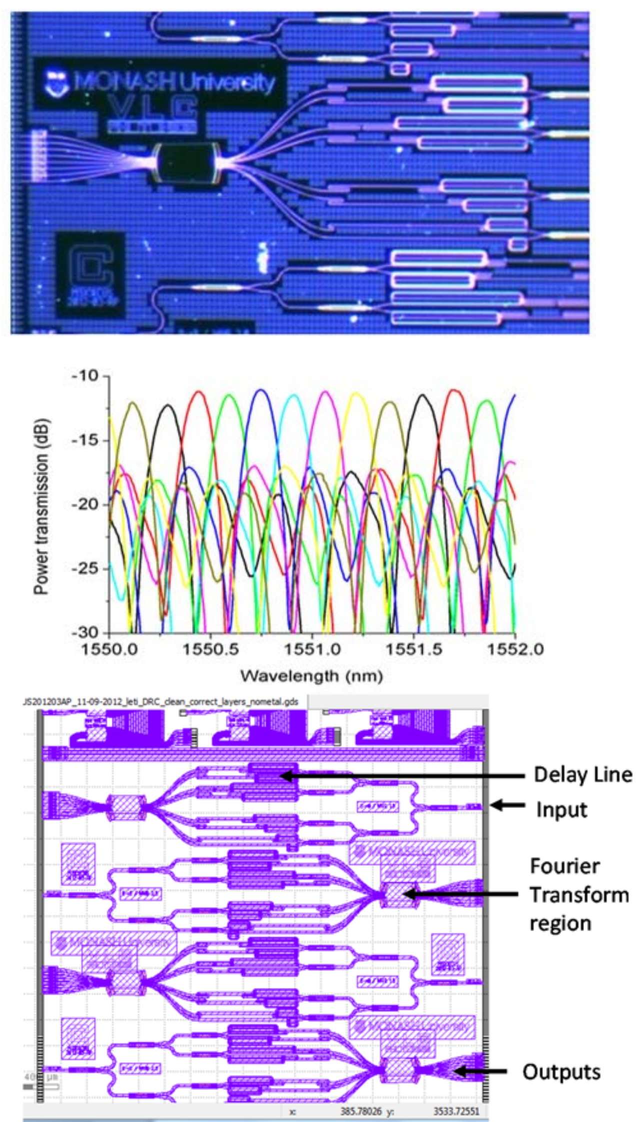

Fig. 11. All-optical Fourier transform chip designed for optical OFDM transmitters and receivers: (top) photomicrograph; (middle) wavelength responses of the individual inputs; (bottom) layout. This design requires external modulators. Note that the race-track delays dominate the area of the chip, and that the slab performing the FT is relatively small as it only has to provide 2π phase shifts. From [49].

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A newer design, shown in Fig 12, uses silicon technology which enables modulators to be incorporated into the chip. This has yet to be characterized.

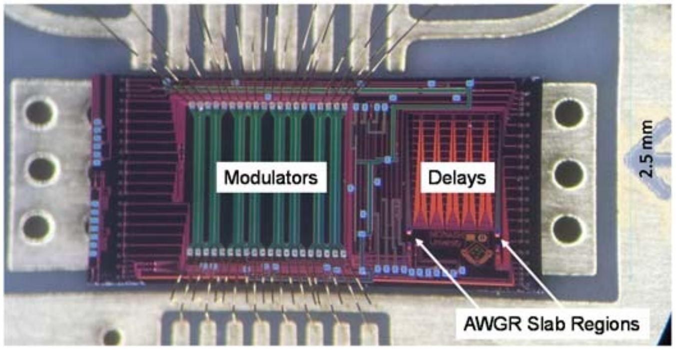

Fig. 12. All-optical Fourier transmitter transform chip including modulators.

IV. Nyquist WDM

Nyquist-WDM maximizes spectral efficiency by tightly filtering each WDM channel to its Nyquist bandwidth (equal to the symbol rate), then packing adjacent channels with little or no guard band between them [4]. As shown in Fig. 13, the pulse shape of a particular wavelength channel is effectively the superposition of many modulated sinc-shaped pulses, with considerable overlap of the pulses. Conversely, in the frequency domain, the wavelength channels have very little overlap, so optical filtering can be used to perform wavelength routing. This filtering can be performed by DSP, before the transmitter's DACs [50-52]. Alternatively, optical processing can be used, such as high-resolution photonic processors based on an AWGR combined with a Liquid-Crystal on Silicon spatial light modulator [53-55].

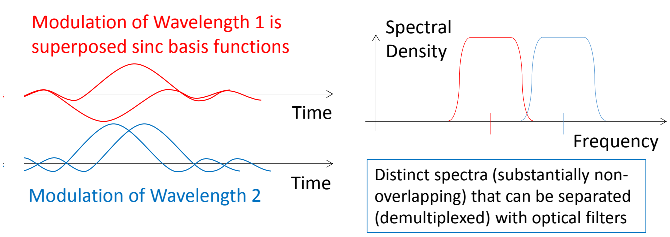

Fig. 13. Waveforms and spectra of two Nyquist-WDM wavelength channels. Note that the waveforms (left) are shown as separate sinc-shaped pulses, that is, before superposition. The spectra of the wavelength channels (right) have very little spectral overlap.

We have recently reported experimental results using a RAMZI photonic circuit (Ring-Assisted Mach-Zehnder Interferometer [56-58]) to shape both data-modulated mode-locked laser pulses and CW wavelengths to give a very narrow spectrum with sharp pass-band to stop-band transitions [59] and to create Nyquist-WDM-like super-channels [60, 61]. As shown in Fig. 14(a), this is relatively compact compared to tapped-delay-line topologies [62].

The RAMZI is an integrated version of a Michelson-Gires-Tournois interferometer [63, 64]. The transmission of Ports 1 or 2 can be written as:

$$T = 0.5\left(1+\cos\left(\frac{2\pi n_g}{c} f\,2\Delta L + \Delta\varphi\right)\right)$$

$$\Delta\varphi = 2\tan^{-1}\left(\frac{1+\sqrt{R_2}}{1+\sqrt{R_1}}\tan\varphi\right) - 2\tan^{-1}\left(\frac{1+\sqrt{R_1}}{1+\sqrt{R_2}}\tan\varphi\right) \quad (3)$$

where f is the optical carrier frequency, ΔL is the length difference noted on Fig. 14a, n_g is the group index of the waveguides, R_1 and R_2 are the effective reflectivities (as controlled by phase shifters 3 & 4), and φ is the phase difference between the two major MZI arms (controlled by phase shifter 6). Reference [59] gives an alternative Z-transform representation of Eq. (3).

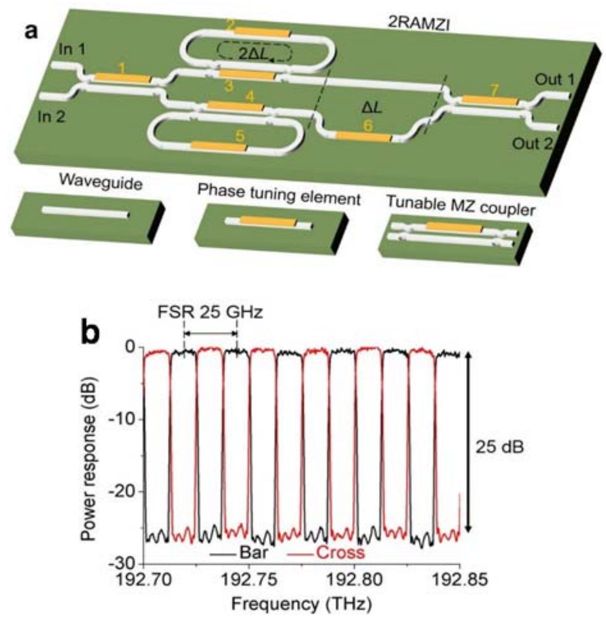

Fig. 14: (a) Ring-Assisted Mach-Zehnder Modulator (RAMZI) chip for generating and demultiplexing Nyquist WDM channels; (b) Typical responses of an optical switch using a RAMZI de-interleaver as a pre-filter for a wavelength selective switch [65]. The Bar (black) and Cross (red) traces correspond to separate chip outputs 1 and 2.

Commercial ROADMs do not have sufficiently sharp pass-to-stop-band transitions to support switching/routing of sub-bands within N-WDM super-channels [66]. Thus wide guard-bands must be used between the wavelength channels, or advanced signal processing used, such as sub-band pairwise coding [65, 67, 68], to mitigate the effect of partially overlapping wavelength channels. We have demonstrated that the resolution of a commercial ROADM can be improved by using a RAMZI interleaver as a pre-processor to split 'odd' and 'even' channels to the inputs of two separate ROADMs [65], shown in Fig. 14(b). One ROADM switches the odd channels, and the other switches the even channels, then these two outputs are combined to regain the full spectrum. The interleaver ensures that each ROADM has large guard bands between its channels, to accommodate the slow pass-band to stop-band transitions of its filters. This approach enables add-drop functionality of zero-guard-band Nyquist WDM channels using commercial wavelength-selective switches based on LCoS technology.

We have recently shown by simulations that Nyquist channels could also be generated using the FT functionality of an AWGR. In this case, the inputs that are presented to the IFT are identical frequency-domain signals (that is, a rectangular spectrum). These inputs are transformed to the time-domain using the FT [69].

V. Other Signal Formats

A. DFT-spread OFDM

Discrete Fourier Transform-spread OFDM (DFT-S-OFDM) uses one or more DFTs placed before the transmitter's inverse FT [70]. These preprocess a single group or several groups of subcarriers, so that the output of the inverse FT has a lower peak-to-average power ratio (PAPR). Each group is assigned to a different portion of the spectrum. A low PAPR is beneficial in long-haul communications links as it should lead to less nonlinear phase shift and lower associated self-phase modulation (SPM) within a wavelength channel and lower cross-phase modulation (XPM) between the wavelength channels [71]. Note, however, that after propagation in dispersive fiber, the PAPRs of OFDM, DFT-S-OFDM and Nyquist WDM tend to converge, so that the "PAPR disadvantage" of OFDM is only relevant for short-haul and dispersion-managed links.

We have simulated optical methods of generating all-optical discrete-FT pre-processed (DFT-OFDM) signals, and proposed improvements [72]. The principle of generating one group in DFT-S-OFDM is to start with a train of periodic sinc pulses. Theoretically, these belong to a train of overlapping unmodulated infinite-extent sinc pulses. Practically, periodic sinc pulses can be generated using a mode-locked laser with its output spectrum truncated to several comb lines, and power-equalized so that each line is the same amplitude [73]. Alternatively a mode-locked laser can have a bandwidth limiting filter within its cavity to produce the same rectangular-comb spectrum—the Nyquist laser [74]. As shown in Fig. 15 (top), the periodic-sinc pulses are then split into several tributaries, then delayed relative one another, modulated, then combined. Because the pulses enter the modulators with different relative delays, but the modulators have synchronized data inputs, the peaks of the periodic sinc pulses appear at different offsets to the start of the OFDM symbols, as illustrated with the two waveforms in Fig. 15 (bottom). A disadvantage is that the modulators have to have fast transitions, particularly when the peak of the sinc falls at the boundary of the OFDM symbol (yellow waveform), though these 'extreme' tributaries could be avoided.

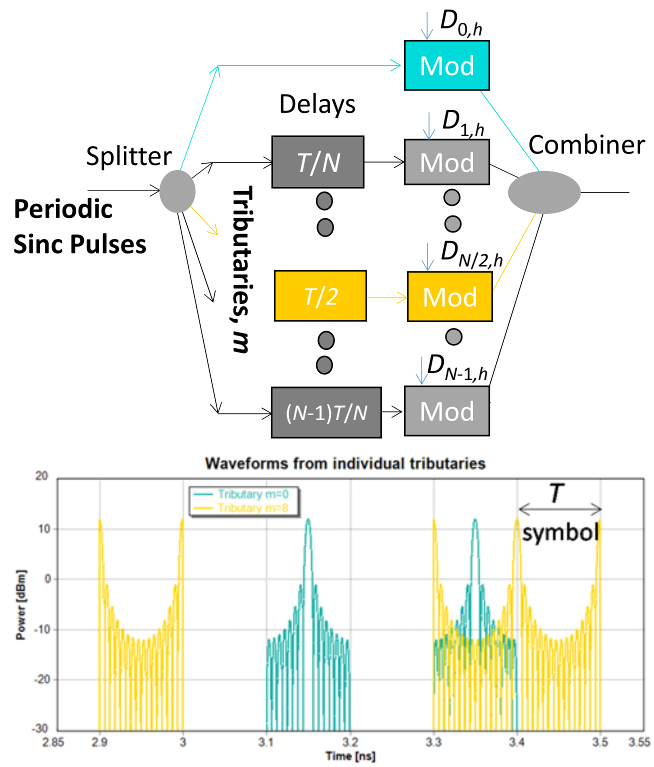

Fig. 15. All-optical DFT-S-OFDM Fourier transmitter [72]: (top) signal processing block diagram; (bottom) waveforms of the blue and yellow tributaries.

The advantage of this scheme over those that center the modulation window around the main peak of each sinc pulse (such as Orthogonal Time Division Multiplexing, OrthTDM [73]) is that, because of their particular spectral features, many groups can be wavelength-multiplexed into a super-channel with a flat-top spectrum without guard bands [72]. A DFT-S-OFDM receiver is similar to an all-optical OFDM receiver except that a second bank of inverse Fourier transforms is required to undo the DFT operation at the transmitter.

B. Fractional Fourier transforms & chirped-OFDM

Fractional-FTs (FrFT) can be used to produce OFDM signals with a chirp across each symbol [75]. Effectively, each subcarrier sweeps up (or down) in frequency during each OFDM symbol. One method of implementing an optical FrFT is to modify the AWGR design to add a quadratic phase shift across the arrayed waveguides [76]. For example, in a transmitter, an inverse FT is used. This has a slab coupler acting as an FT, followed by a parallel-to-serial converter. The phase shift can be added by modifying the radius of the input side of the slab coupler, as shown in Fig. 16 (green). Alternatively, the lengths of the waveguides can be adjusted slightly. Because the arrayed waveguides and second slab are acting as a parallel-to-serial converter, the phase shifts are effectively applied to the sequential samples of the output waveform, so add a chirp to it.

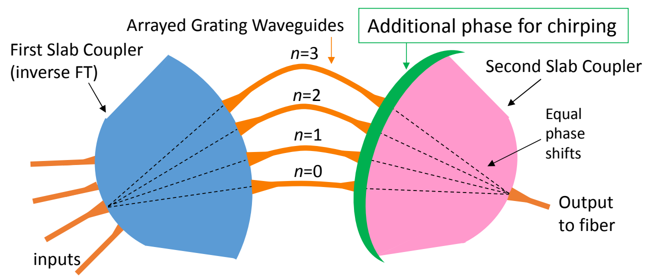

Fig. 16. One method of producing 'chirped-OFDM' where the subcarriers all have a frequency chirp imposed upon them at the transmitter.

C. Quasi-NWDM

The frequency sweeping of the chirped-OFDM subcarriers during each OFDM symbol enables them to be manipulated using a dispersive fiber [76], in a similar fashion to optical processing using 'time-lenses' [77, 78]. For example, if the chirp is from redder to bluer (both, of course, infra-red), a standard single mode fiber will speed up the bluer parts relative to the redder parts, providing pulse compression. This can be used to create sinc-like pulses from chirped OFDM subcarriers, which we call 'quasi-NWDM' [79]. Multiple sets of sinc pulses can be interleaved if they sets are delayed relatively to one another. As shown in Fig. 17(a), this can be achieved by having multiple inputs to the first slab, at different positions [76]. These are effectively different frequency inputs to the inverse FT, and so will be assigned to different central frequencies relative to one another. These frequency offsets mean that the sets of pulses will acquire different delays in the dispersive fiber, so that they become interleaved in time. We have previously shown that the associated spectrum of chirped-OFDM/quasi-NWDM is not suitable for creating super-channels as it has wide tails: a better spectrum can be obtained using an optical-time division multiplexer (OTDM) as a preprocessor, connected to a single input to the first slab coupler, as in Fig. 17(b) [79]. This creates a spectrum with a Fresnel shape, which is analogous to the far-field pattern of an aperture illuminated by a point source behind it. The width of the spectrum can be reduced further if the chirping is forgone, for example, if the sinc pulses are generated (with some truncation) using a finite-impulse response filter, as shown in Fig. 17(c). In this case the spectrum is a rectangular function convolved with a sinc function [79].

Nagashima *et al.* have shown that fiber nonlinearity can be mitigated using fractional Fourier transforms, by letting the signal format oscillate between chirped-OFDM and quasi-NWDM along a dispersion managed fiber [80]; for example, by ensuring that the signal has a low PAPR just after each optical amplifier.

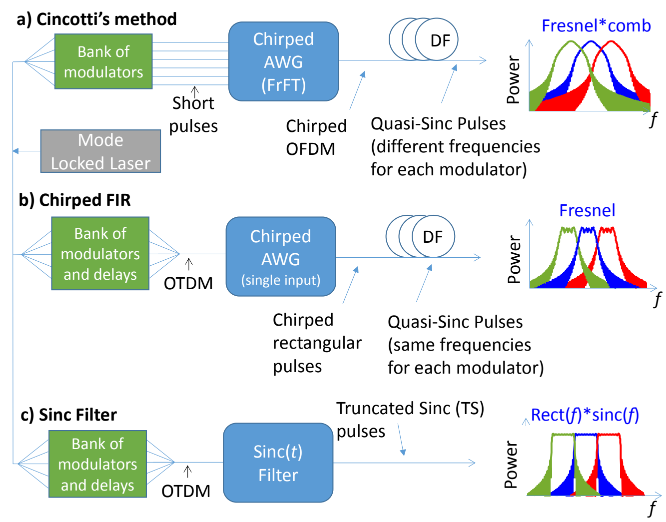

Fig. 17. Comparison of methods to generate chirped (a, b) and unchirped (c) pulses, and their associated spectra. Redrawn from [79].

VI. Conclusions

In this paper we have discussed how many types of optical communications signal can be produced by optical filtering (or pulse shaping) modulated optical pulse streams, using photonic integrated circuits. For optical OFDM, this modulate-then-filter approach is preferential to pulse shaping in the electrical domain and modulating individual wavelengths, as this would require very high bandwidth modulators. In OFDM systems, the optical filters can be formed using modified arrayed-waveguide grating routers (AWGR), which implement an inverse Fourier transform followed by a parallel-to-serial converter. For Nyquist WDM, the filters have to have long sinc-like impulse responses, and the ring-assisted Mach-Zehnder modulator (RAMZI) is suitable for both pulse shaping and demultiplexing Nyquist-WDM signals.

We have also discussed the generation of DFT-spread OFDM, by delaying and then modulating periodic-sinc pulses; unfortunately, this technique again requires very fast modulators, but does give signals that can be wavelength-multiplexed into superchannels. Chirped-OFDM, created by modifying the AWGR Fourier transform to become a fractional Fourier transform, can be converted into quasi-Nyquist WDM using a simple dispersive fiber (and back again using a dispersion compensating fiber). We have proposed a simple modification to the scheme proposed by Cincotti to produce an optical spectrum that is more suitable for dense wavelength packing into superchannels.

Overall, using optical filters for the generation, processing and reception of wide bandwidth optical channels is advantageous because of their extremely wide bandwidths and low power consumption (generally the power required for the optical amplifiers to compensate the filters' losses). A perceived limitation is the resolution of the filter (or the limited duration of its impulse response); however, the general trend of increasing symbol rates of modulation is mitigating this limitation, and the RAMZI filter, with its infinite-impulse response rings, does provide a particularly long impulse response for its size.

Another driver for the adoption of optical filtering and pulse shaping is the growing maturity of photonic integrated circuit foundries. Several open-access suppliers are now available, and the more that they are used, the more mature their technologies will become. Given the need to miniaturize optical subsystems, so that they can be incorporated into pluggable optical modules, the future for the photonic integrated circuit industry looks bright.

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