Application of Photonic Circuits 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 investigates how photonic circuit topologies have evolved to support high-spectral efficiency modulation formats.

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1. Introduction

Optical OFDM [1] and Nyquist WDM [2] both support high spectral efficiencies by either enabling the subcarrier to overlap without crosstalk, or by tightly controlling the spectral extent of each channel, respectively, using digital and/or photonic processing [3]. Electronic generation of these signals can provide flexibility, but at a significant energy cost for the high-speed digital-to-analog converters. Electronic demultiplexing requires oversampling to select a particular channel from its neighbors, and is usually combined with optical demultiplexers as a first stage. That said, many originally optical processing functions, such as dispersion compensation using dispersion-compensating fiber, are now performed by digital signal processing (DSP) – as DSP enables a much simplified link design with no inline dispersion compensators, much reducing back-office engineering support, and increasing upgradability. DSP can also provide some compensation of fiber nonlinearity (NL) [4, 5].

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 (funded by the Australian Research Council grant FL130100041), and we have assembled a team with experience encompassing photonic and electronic circuit design methods to achieve this goal.

This paper investigates the work of our team and, to the extent possible in a short paper, 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, we have recognized that hybrid signal formats, spanning OFDM to its 'dual' N-WDM could offer the best of all worlds.

2. Photonic circuits as for signal shaping

This paper will concentrate on the linear functions within photonic circuits, which provide the specific filtering and pulse shaping necessary to generate N-WDM and OFDM—because sources, modulators, samplers and receivers are common to all modulation formats. The filter designs nearly always use discrete paths for the optical signals so, to a good approximation, provide impulse responses that are sums of delta functions —as is common in digitally processed electronic signals, which are inherently sampled for clocked computation.

The discrete nature of the paths enables signal processing know-how to be used in photonic circuit design, such as well-described by Madsen and Zhao [6], and this assumption is also implicit when numerically modeling photonic circuits. Having only discrete paths considerably simplifies the designs conceptually, enabling the design to be performed at a higher level: for example, an arrayed waveguide grating router can be abstracted to a serial-to-parallel converter followed by an $n\times m$ phase-shift matrix (implementing a Fourier transform, FT [7]); a topology that is well known to conventional OFDM designers as the basis for OFDM receivers [8], and in-reverse for transmitters [9].

Although there are discrete paths, the optical signals passing through the circuits are continuous in nature, and because they are not sampled, they have almost unlimited bandwidth. Herein lies a key advantage of optical signal processors. However, the continuous nature of the optical circuits can be modified; for example, in transmitters, trains of short pulses can be sourced from a mode-locked laser, so the photonic circuit appears to operate on discrete samples. Fiber transmission will generally spread these samples into a continuous waveform via dispersion; thus, at the receiver, these continuous signals need to be sampled optically or electronically, so that the output of the photonic circuit is only observed when it is optimum. Here, optical sampling is advantageous over electrical sampling if extremely wide bandwidths have to be processed, as the sampling gate-width must be a few picoseconds at most. Of course, all digital communications systems also use samplers to get back to 'bits', thus sampling is not peculiar to optical processing—that is, the need to sample after an optical FT is not strictly a disadvantage of optical processing.

3. Photonic circuits for all-optical OFDM

Optical OFDM transmits subcarriers in 'blocks' or OFDM symbols, with their modulation being synchronized so that all transitions align at the receiver [10]; the modulation amplitude and phase also has to be constant throughout the symbols. The receiver uses matched filters with finite impulse responses (FIR) to demultiplex the subcarriers, and samples the output of each matched filter once per symbol, when the 'window' of the matched filter aligns with the symbol (i.e. the filter is processing the signal from only one symbol). The frequency spacing of the subcarriers is arranged so that they are all periodic within the receiver's window. Thus, the subcarriers can be recovered without inter-(sub)-carrier-interference (ICI). A discrete 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.

An all-optical OFDM transmitter can be implemented by either: (a) modulating the outputs of CW lasers (or tones demultiplexed from a comb source), then combining, or (b) modulating pulses from a mode locked laser, then 'shaping' with a filter to create each subcarrier [9, 11]. Method (a) requires very high bandwidth modulators, otherwise the amplitude and phase in each subcarrier will vary during a symbol, causing loss of orthogonality. Method (b) relaxes the modulator's bandwidth, because the modulator need only be in the correct 'state' as the pulse passes through it [11]. This technique has been demonstrated with Liquid Crystal on Silicon (LCoS) technology [12]. It is also possible to modify an Arrayed Waveguide Grating (AWG) design to approximate a flat-top impulse response to provide an inverse FT with a rectangular window function suitable for OFDM [7, 11, 13].

The receiver's processing can be achieved in the electrical domain, but at a bandwidth limited by the sample rate of the DACs. Thus, for super-channels at least, optical processing is necessary. This can be achieved using AWG-based FTs [8, 14-16], or FT's using a network of 2×2 couplers [17-19], with a similar 'butterfly' topology to a DSP "fast" FT [20]. In both cases, a fast sampler is required, which can be optical, or possibly electrical, providing the sampler has a bandwidth in excess of the entire subcarrier spectrum, which is challenging. To create superchannels with low Peak-to-Average Power Ratios (PAPRs), we have proposed optical methods of generating discrete-FT pre-processed (DFT-OFDM) signals [21], which promise increased tolerance to fiber nonlinearity [22]. Overlapping DFT-S-OFDM channels (*Faster than Nyquist*) is also possible [23].

4. Photonic circuits for Nyquist-WDM

Nyquist-WDM maximizes spectral efficiency by tightly filtering each WDM to its Nyquist bandwidth (equal to the baud rate), then packing the channels with little or no guard band [2]. This filtering can be performed by DSP, before the transmitter's DACs [24, 25]. We have recently reported experimental results using a RAMZI photonic circuit (Ring-Assisted Mach-Zehnder Interferometer) to shape data-modulated mode-locked laser pulses to give a very narrow spectrum with sharp pass-band to stop-band transitions [26], and to create superchannels from [27].

Generally, commercial ROADMs do not have sufficiently sharp pass-to-stop-band transitions to support switching of N-WDM superchannels. Thus wide guard-bands must be used between the 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 separate ROADM inputs [28]. This approach enables add-drop functionality of zero-guard-band Nyquist WDM channels using commercial wavelength-selective switches (WSS) that use LCoS technology. We have also demonstrated that a single WSS can assign modulated-pulse inputs to multiple signal formats carried by a single output fiber [29], at any set of wavelengths, on or off a frequency grid [30]. This is especially useful to validate that installed optical links can carry new signal formats along with legacy channels.

5. Other signal formats – between N-WDM and OFDM

Fractional-FTs can be used to produce OFDM signals with a chirp across each symbol [32], which evolve between chirped-OFDM and Nyquist-OTDM [33] formats along a dispersion-managed link [34], to minimize the effects of fiber nonlinearity. We have shown that the associated spectrum can be predicted using the Fresnel equation, and that a more confined spectrum can be obtained using an optical-time division multiplexer (OTDM) as a preprocessor [35].

6. Discussion and Conclusions

Photonic circuits are increasing in functionality, driven by bandwidth and miniaturization demands. The rate of progress will accelerate as more applications require photonic circuit technologies—this will drive up yields and reduce costs. Another driver will be the trading of photonic circuit 'IP', as in electronic chip design. For example, it would be desirable to be able to purchase mode-locked lasers, samplers and modulator designs, each with a guaranteed performance, to combine with custom filter designs. This trading is starting to happen as the supply chain matures, with the emergence of design houses that can take circuit-level designs and transform them into circuit layouts.

7. References

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