Electro-Photonics

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Abstract: I introduce a new field: electro-photonics, where the best of the electronic and photonic technologies are combined to increase the capacity, flexibility and energy efficiency of communications systems.

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1. Introduction

In optical communications research, a common justification for funding all-optical processing is that the electronics is too slow to support high data rates. While there can be some validity in this statement, it has often been used to dismiss the contribution that electronics could make to upgrading communications bandwidth. Conversely, photonic signal processing might be dismissed as being inflexible, compared with electronic digital signal processing (DSP).

The truth is that both electronic and photonic technologies are advancing rapidly. At any particular instant, there will be a different optimal mix of these technologies. This mix will also be influenced by non-technological factors—for example, digital signal processing for dispersion compensation eliminates the need for back-room engineering to plan the dispersion maps of long-haul links, so overcomes a labor shortage.

The aim of the *Electro-Photonics Laboratory* at Monash University, Australia, is to consider the best mix of optical and electronic technologies to produce an optimal solution for a particular problem. We've focused on the optical communications problem space, mainly because of familiarity and experience, though we also consider fundamental building blocks that are generally available in electronics, but are yet to have photonic equivalents.

This paper provides some examples of how we have brought together electronic and photonic technologies, developed sub-systems, and put together experimental demonstrations.

2. Optical transmitters

The optical transmitter obviously includes both electronic and optical components, as it performs a conversion between these domains. Due to my ten-year interest in optical OFDM [1-3], which essentially transmits an analog optical waveform, most of our designs include electronic digital-to-analog converters often feeding complex (or single-sideband) optical modulators. The designs are often energy hungry—FPGAs, Digital-to-Analog Converters (DACs) and driver amplifiers—and/or optically lossy (due to using the 'linear in field' region around a null).

We are working on designs of optical modulators that do not require DACs. One simple method is to use a counter-propagating modulator [4]. Here the optical signal is fed into the opposite end of a $LiNbO_3$ modulator to the electrical signal. The optical phase change is then a finite-duration integral of the electrical waveform. This means that a pulse-width-modulated electrical waveform is converted to an analog phase change, which can then be converted to an optical intensity variation using a Mach-Zehnder interferometer (MZI). Another DAC design is to segment the electrical electrode of a conventional modulator, usually into a power-series such as lengths of 1, 2, 4, 8 units [5]. This design requires multiple drive amplifiers and possibly terminations, though designs have been proposed without terminations. An example of one of our Photonic Integrated Circuits (PIC) is shown in Fig. 1.

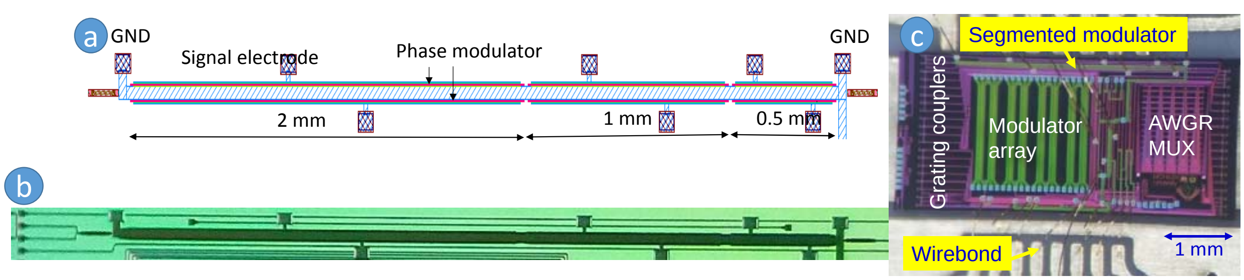

Fig. 1. PIC design of a multi-segment modulator: (a) modulator layout, (b) photomicrograph of the modulator, (c) device realization, integrated with multiple functional building blocks on a single silicon chip.

We have also developed 'universal' transmitters in which an optical processor shapes optical pulses to define their spectra and central wavelength [6]. Our preferred approach is to modulate pulses from a mode-locked laser with one or more modulators; the advantage is that the modulator need only be in the correct state when an optical pulse passes through it. Thus, for example, ringing and slow transitions of the electrical drive waveforms may not matter. The shaping can be achieved by a Waveshaper™ for example, and interestingly, the modulation forms a 'white' spectrum, so the modulated signal can be assigned to any (or multiple) wavelengths—not just the frequencies of the mode-locked laser's comb spectrum [7]. The shaping can also simultaneously different modulation formats, such as Nyquist-WDM, Optical Time-Division Multiplexing and Optical OFDM. This is very useful for loading the C-band with a variety of test channels, but could also be used for format conversion.

Whist the Waveshaper provides flexibility, we have also demonstrated PICs for creating multi-wavelength transmitters. With some modifications, Arrayed Waveguide Grating Routers (AWGRs) can be used as (inverse/forward) optical Fourier transforms (with inbuilt parallel-serial/serial-parallel conversion), and so are the basis of all-optical OFDM transmitters and receivers [8-10]. We have also shown that Ring-Assisted Mach-Zehnder Interferometers (RAMZIs) produce near-Nyquist pulses with very sharp roll-offs [11], and can also be used to upgrade the spectral efficiencies of wavelength-selective switches (ROADMs) [12].

3. Electro-optic fiber nonlinearity compensation

Most forms of optical nonlinearity (Four-Wave Mixing, FWM; Cross-Phase Modulation, XPM; Self-Phase Modulation, SPM) are manifestations of the Kerr effect, where the phase is perturbed by the sum of the instantaneous intensity of the optical signals. Traditionally, nonlinearity can be 'undone' by optical phase conjugation—most commonly mid-span spectral inversion (MSSI), where the second half of the link propagates the conjugate of the first, so the nonlinear effects of each half mostly cancel [13]. More recently, Digital Back Propagation (DBP) has been studied to cancel SPM and/or XPM, though is computationally expensive [14, 15].

Our "Electro-Optic" approach is surprisingly simple: we detect the total intensity all (or groups) of wavelength channels in WDM systems with a single photodetector; we then undo the Kerr phase shift in all wavelengths with a single phase modulator [16]. The surprise is that the photodetector does not need terahertz of electrical bandwidth, indeed it only requires a few gigahertz of bandwidth. This is because walk-off in the fiber restricts the bandwidth of the XPM and FWM effects, so that only GHz frequencies cause significant XPM and SPM. This observation can also be used to increase the computational efficiency of DBP algorithms. Recently, we have been studying the use of multiple compensators along the length of a system, and the effect of polarization on this technique [17].

4. Optical implementations of electronic sub-systems

Many techniques in microwave engineering can be 'upconverted' in frequency to optical carriers. Indeed, microwave engineering has been the inspiration for optical techniques, particularly during the early years of optical communications where many engineers had a microwave background.

One problem with coherent optical systems is creating a compact tunable laser that also has a narrow linewidth and can be tuned rapidly, for a local oscillator. A similar situation occurred with radio receivers in the 1950's, where tuned-circuit local oscillators (LC oscillators) could not provide the stability to remain tuned on narrow-bandwidth military audio channels: the alternative was fixed crystals. The *Wadley Loop* ingeniously solved this issue by combining the stability of a single crystal with the wide-tunability of an LC oscillator [18]. Recently we have demonstrated the same approach in an electro-optic system, where the stability of a mode-locked laser is combined with a widely-tunable laser, using multiple mixing processes [19]. This means that the variable-frequency outputs of multiple tunable lasers can be quantized to the comb-spectrum of a single mode-locked laser, which could be the master oscillator for a whole exchange, or indeed, network.

Another common electrical circuit locks a clock to a data stream—clock recovery. This relies on a phase detector. Our electro-optical equivalent is a delay discriminator, which compares the timing of incoming optical pulses to locally generated clock pulses [20]. Our integrated device generates a slowly varying electrical output (kHz rates) compared to the GHz rates of the optical pulses. This is achieved by counter-propagating optical pulses within an optical amplifier; the first pulse to enter the amplifier gets the most gain: the second pulse sees the depleted gain due to the first pulse. Thus by measuring the relative intensities of the output pulse trains on a long timescale, their relative timing can be determined.

5. Electro-photonics in optical receivers

Digital Signal Processing is now commonplace in optical receivers, primarily because higher-order QAM modulation requires equalization and phase recovery to produce clear constellations. DSP is also used for dispersion compensation, and is increasingly used for nonlinearity compensation [15]. Our interest has been in pairwise coding, where data is interleaved across ‘good’ and ‘bad’ channels to provide a better overall BER than simply adding the BERs of the two independent channels. We first considered good and bad channels in direct-detection optical-OFDM systems [21]. A more common application is across good and bad polarizations in polarization-multiplexed systems with polarization-dependent loss [22], or for side and edge subcarriers passing through ROADMs [23].

6. Conclusions

Electro-photonics benefits from considering combinations of photonic and electronic technologies to address current problems in generating, processing and receiving high-rate data communications channels. PICs can provide very wide bandwidth processing, but surprisingly, slow electronics can also improve such channels. A valuable lesson from our work is that it is best to have teams that are well schooled in diverse areas, such as communications theory, photonic technologies, and electronic and microwave sub-systems, in order to make innovative advances.

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