Multi-Channel Comb Modulation in Single Waveguide Structures

Mikael Mazur(1), Nicolas K. Fontaine(1), Haoshuo Chen(1), Roland Ryf(1), David T. Neilson(1), Gregory Raybon(1), Andrew Adamiecki(1), Steve Corteselli(1) and Jochen Schröder(2).

(1) Nokia Bell Labs, Crawford Hill, 791 Holmdel Rd, NJ 07733, USA mikael.mazur@nokia-bell-labs.com
(2) Photonics Laboratory, Chalmers University of Technology, SE-41296, Sweden

Abstract *Lossless modulation based on unitary spectro-temporal transformations allows modulation of independent waveforms onto lines from a frequency comb without any DeMUX/MUX. We discuss this alternative modulation technique and its application in optical communication and frequency comb generation.*

Introduction

Optical IQ-modulators are one of the key components in modern optical communication systems. In contrast to directly modulated lasers, IQ-modulators enable simultaneous modulation of both the amplitude and phase of a lightwave[1]. The most widely used structure consists of two nested Mach-Zehnder interferometers, configured as single dimension intensity modulators, to independently modulate the I- and Q-component of the field. The Q-component is then phase-shifted by $\pi/2$ and the two quadratures are combined using a 3 dB coupler[1]. Optical modulators are also used to generate frequency combs[2],[3].

MZM-based IQ-modulators are easy to use, with a direct mapping between the electrical driving signal and the resulting envelope. However, MZM-based IQ-modulators are inherently lossy. The nested structure has a minimum theoretical loss of 3 dB[1]. This not only requires additional amplification but also prevents their usage in areas requiring unitary spectro-temporal transformations such as quantum optics[4],[5]. Modulation via energy carving furthermore adds loss for any multi-level format/waveform such as higher order quadrature amplitude modulation (QAM) or a pulse-shaped signal. More critically, while the optical bandwidth of an IQ-modulator typically is very large, it modulates every injected laser line with an identical envelope. This drastically increases the complexity of frequency comb-based transmission system by requiring N modulators and a DeMUX-MUX combination, increasing the complexity of multi-channel transmitters[6].

Alternatively, temporal modulation can be achieved by redistributing the energy from an input waveform, such as a continuous wave laser, into the target output waveform[7]–[9]. In general, this cannot be achieved using a single modulation stage but instead requires multiple cascaded reshaping stages. Each stage can be seen as a generalized time-lens consisting of temporal followed by spectral phase modulation. Importantly, phase modulation is theoretically loss-less and IQ-modulation via temporal transformation can therefore be used without inferring any fundamental loss in the system. By jointly optimizing the modulation in each stage, the output waveform is synthesized[8]. Importantly, this modulation principle can be used to generate independent output waveforms onto multiple spectrally separated input laser lines[10]. It can also be used to create frequency combs with arbitrary shapes[11].

Modulation Principle

A schematic for the proposed modulator together with the traditional MZM-based IQ-modulator is shown in Fig. 1. It consists of multiple stages arranged in a single waveguide structure. All input lines are therefore modulated at the same time. Each individual stage consists of temporal phase modulation $\phi(t)$ followed by spectral phase modulation $\beta(\omega)$, i.e., dispersion. First, temporal phase modulation adds new frequency content to the signal. These frequency components are then dispersed by the spectral phase modulation, which implements phase-to-amplitude conversion. This process is then repeated to gen-

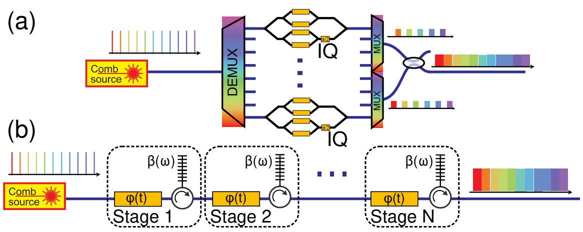

Fig. 1: (a) Schematic of a traditional comb-based WDM system using a DeMUX-MUX combination and N independent MZM-based IQ-modulators. (b) Proposed multi-channel modulator using multiple cascaded stages of temporal and spectral phase modulation to simultaneously modulate each input line with an independent waveform.

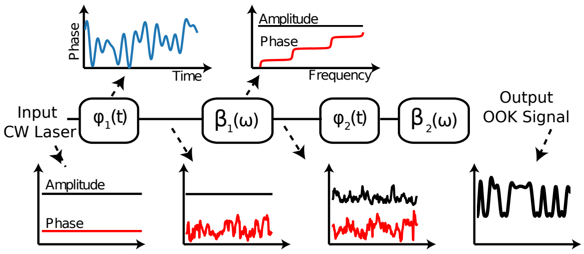

Fig. 2: Modulation principle: An input CW-laser is modulated to a binary on-off keying (OOK) signal using two stages[8].

erate the resulting output waveform. Note that there are, in principle, no restrictions on shape of the temporal nor the spectral phase modulation. However, for simplicity, we used a fixed quadratic dispersion profile throughout this work. The simultaneous multi-wavelength modulation capabilities can be understood using the same principle. While the temporal phase modulation is common for input signals on different wavelengths, the response from the spectral modulation is not. Given this, the response of each stage is unique, enabling the buildup of independent output waveforms. Importantly, depending on the relative target signal bandwidth/dispersive length response, the number of required stages will vary[9]. It is also possible to generate a multi-channel output waveform starting from a single line although the number of stages needed will be significantly larger. This process can be understood by jointly consider the comb generation and multi-channel capabilities of the proposed method discussed in the following sections. Importantly, the amount of dispersion is inversely proportional to the bandwidth square. A doubling of the symbol rate therefore reduces the amount of dispersion needed by a factor of four.

Finding the Phase Modulations

This modulation approach relies on finding a combination of phase modulations that, interleaved with dispersive elements, implements the sought input-output temporal transformation. Since this transformation is loss-less, the same structure applied in reverse would work as a modulation stripper. To the best of our knowledge, there are no direct methods for performing the optimization required to find the phase modulations which guarantees a unique solution. In this work, we rely on inverse design/a modified wavefront matching algorithm to approximate a solution[12]. The principle is based on defining a forward and backwards propagating wave and the optimizing aims at produces a solution where the forward and backward propagating waves overlap at each point in the system. The error is calculated via

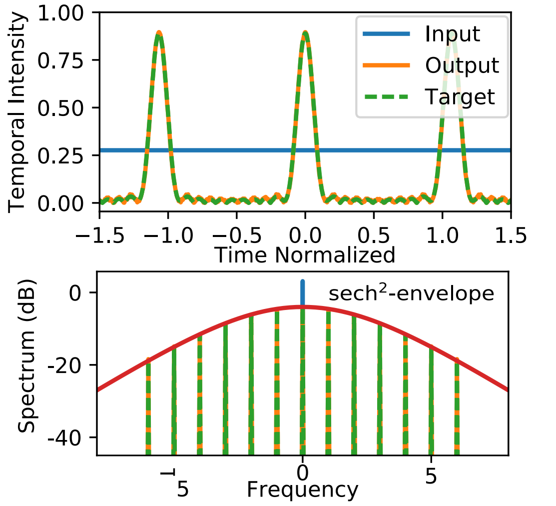

Fig. 3: Simulated bandwidth limited frequency comb with Sech^2 envelope with 13 lines generated from input CW laser using 11 stages[11].

the overlap integral of the temporal waveforms at a given stage k, subject to the phase modulation $\phi_k(t)$ according to

$$o_k(t) = f(k\Delta z, t) b(k\Delta z, t)^* \exp(j\phi_k(t)), \tag{1}$$

with f, b denoting the forward/backwards wave and Δz the distance between the stages, mapping to the amount of spectral phase shift added. The error is then minimized using a standard gradient decent algorithm. In general, we found that about 100 iterations were needed to achieve a good convergence and no improvement was seen after about 500 iterations. However, more optimized ways of designing the phase modulations is a topic of ongoing research and the method used here is by no means unique. Similarly, the solution is not unique. However, high quality solutions that are implementable are observed to share common features such as being smooth.

Implication of Space-Time Duality

The modulator presented here is also the temporal equivalent of the spatial mode-multiplexer based on multi-plane light propagation (MPLC)[13],[14]. Similarly to how MPLC can be used to simultaneously convert multiple spatially separated input beams to orthogonal spatial modes, our modulator converts multiple spectrally separated inputs to modulated orthogonal output waveforms. The space-time duality arises from the equivalence between the equations describing pulse propagation in an optical fiber subject to dispersive broadening and the propagation of beams in free space governed by paraxial diffraction[15]. For the

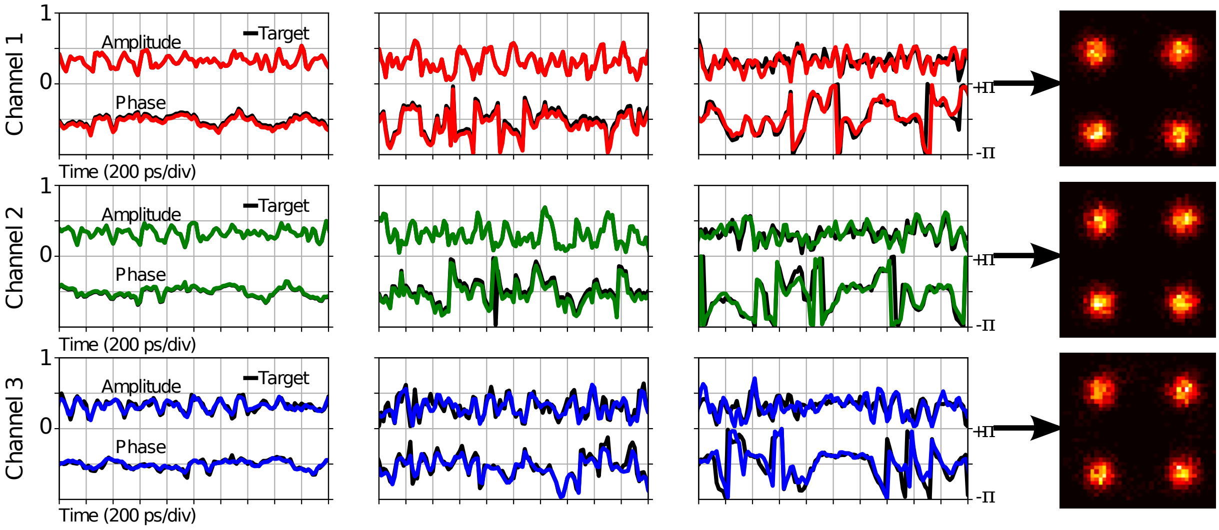

Fig. 4: Measured output waveforms simultaneously modulated onto three lines originating from a frequency comb without the use of a DeMUX-MUX combination[9]. The transformation was implemented with 8 stages and the output signals are shaped with a 1% roll-off root-raised cosine filter.

proposed modulation structure, the duality give raise to two interesting analogs. First, each segment can be seen as a generalized "time lens". In contrast to the "time lens" which use quadratic dispersion and phase-modulation to achieve a temporal Fourier transform[16],[17], each stage in our method use modulations of arbitrary shape, thereby implementing a generalized transformation.

Frequency Comb Generation

As previously mentioned, one application of optical modulators is the generation of frequency combs. The general transformation properties of the proposed method can therefore be used to generate combs with programmable spectral/temporal shapes[11]. One simulated example of such frequency comb generation is shown in Fig. 3. The target waveform has the sech^2 envelope, similar to Kerr frequency combs generated in microresonators. However, while a microring comb would distribute the energy among all lines, we can tailor the phase modulations to instead redistribute the energy to the selected bandwidth, which here is 13 lines. The transformation was implemented using 11 stages starting from a CW input. In addition, a few segments of the proposed method could be used as temporal pulse shaper to achieve a given, general, target pulse shape. In this case, the input could be the output of a frequency comb, and the output would be a train of pulses with a new temporal shape.

Multi-Channel Modulation

Arguably the most impressive feat of the proposed modulation structure is its ability to modulate independent waveforms onto spectrally separated input lines[9]. The target waveforms were 4-QAM signals shaped with a 1% roll-off root-raised cosine filter. Note that while 4-QAM can be implemented using a single phase-modulator, a shaped 4-QAM signal requires an IQ-modulator. The measured output waveforms modulated onto three input lines from an optical frequency comb is shown in Fig. 4. The transformation was implemented using 8 stages and the output after stage 1,6 and 8 are shown together with the resulting constellation diagrams. We observed a good overlap between the measured and target waveforms and the constellation diagrams verify the high quality of the generated waveforms. In this proof-of-principle experiment, presence polarization mode dispersion limited the number of simultaneous channels that could be modulated. While the exact scaling laws in terms of number of required stages require additional research, we note that simulations indicate that about 10 wavelength channels with 4-QAM or 8 with 16-QAM should be implementable using about 10 stages.

Conclusions

Unitary transformations of spectro-temporal modes are not limited by the same constraints as traditional MZM-based IQ-modulators. We discussed this alternative way to achieve arbitrary waveform generation/IQ-modulation and its implications for communication systems and frequency comb generation. This has the potential to enable new applications in areas such as super-channel generation, arbitrary optical pulse shaping and quantum optics.

Acknowledgements

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