## Rapidly reconfigurable optical channel selector using RF digital phase shifter for ultra-fast OTDM networks

K.-L. Deng, D.T.K. Tong, C.-K. Chan, K.F. Dreyer and J.E. Johnson

An RF photonic scheme capable of performing channel tuning among time slots in ultra-fast OTDM networks at nanosecond reconfiguration speed is described. In the demonstration, demultiplexing across ten OTDM channels from a 100Gbit/s signal stream was achieved at a reconfiguration time of 4ns with simple ECL logic control.

Introduction: Recent advances in optical time division multiplexing (OTDM) have shown the potential to increase the single channel bit rate from 40Gbit/s to hundreds of gigabits per second [1, 2]. In conjunction with the WDM approach, OTDM can further increase the total aggregate capacity to terabits-per-second regime with a few wavelengths [3]. However, in order to perform channel add-drop efficiently, rapid switching among a large number of channels becomes essential, which leads to the development of reconfigurable transmitter and receiver that are rapidly tunable in either the wavelength or time domain. Tunable OTDM transmitters based on a modelocked laser diode and a gain-switched DFB laser have been demonstrated [4, 5]. In this Letter, we describe a rapid channel demultiplexing/selection scheme for ultra-high speed reconfigurable OTDM networks. The scheme is based on an RF digital phase shifter for channel selection and electro-absorption (EA) modulators for channel demultiplexing. In our experiment, we demonstrated channel selection and demultiplexing among ten 10Gbit/s OTDM channels from an aggregated traffic of 100Gbit/s. The intrinsic switching speed for the channel selection device is ~1 GHz while the overall reconfiguration time is 4ns, limited only by the ECL control logic used to drive the RF switches. The same circuit can be readily applied to 160Gbit/s OTDM systems.

EA modulators have been used to provide ultra-short gating windows that are suitable for pulse generation and demultiplexing at 80 and 160Gbit/s OTDM systems [6]. To generate a short gating window in the time domain, a sinusoidal RF signal at the channel bit rate is used to drive the properly biased EA modulators. This opens the opportunity to select desired ultra-short time slots (channels) by shifting the phase of the RF driving signal. Here we propose to use a fast RF digital phase shifter to adjust the phase of the RF driving signal within a few nanoseconds, thus allowing fast channel selection to be achieved. The RF digital phase shifter is an RF-switched delay line circuit, which provides a precise discrete phase shift according to simple digital control logic. The fast channel reconfiguration can then be achieved by properly setting the state of the RF switch in each stage of the delay line, causing the RF driving signal to experience different time delays which results in discrete phase shifts. Hence, the phase-shifted RF driving signal will set the EA modulators to perform the optical processing at the selected time slot. Compared to a similar approach that has been demonstrated by cascading optical modulators and switches [7], our approach is polarisation-independent, free of the optical power budget problem and potentially cost-effective.



Fig. 1 Schematic diagrams of fast reconfigurable demultiplexer using RF digital phase shifter and EA modulators

SW: RF pin diode switch, OBF: optical bandpass filter, PS: RF power splitter

Experiment and results: Fig. 1 shows a schematic diagram of the experimental demonstration. The digital phase shifter consists of multiple stages of differential delay lattices and each lattice has a time delay of  $2^{k-1}\tau$  for the *k*th stage, k = 1, 2, ..., N. For an *N*-stage device, the corresponding differential phase at the kth stage is  $(2^{k-N-1})\pi$ . A single-pole double-throw  $(1 \times 2)$  pin diode switch is inserted in between the adjacent lattices. The intrinsic switching speed of the diode switch is ~1 GHz. At each RF switch, an ECL driver is interfaced with the control signal for output phase control. Digital sequences  $[J_N, ..., J_2, J_1]$  set the corresponding states of all N RF switches and determine the final output phase of the device. For example, in the case of N = 4,  $[J_4, J_3, J_2, J_1] =$ [0001] will set the output phase to be  $1/16\pi$  (phase 1 for channel 1) and [0011] for  $3/16\pi$  (phase 3 for channel 3), and so forth. In the demonstration, a four-stage device is constructed using discrete components, which can provide up to sixteen states of output phases. The 16dB loss through the device is compensated using an RF amplifier.

As shown also in Fig. 1, we use a 100Gbit/s OTDM setup to demonstrate the proposed scheme. A modelocked fibre ring laser generates 10Gbit/s optical pulses with a pulsewidth of 2ps. NRZ data with a word length of  $2^{31}$  – 1 is encoded on the pulse train and converted into RZ format. The 10Gbit/s RZ pulses are then time-mutiplexed to 100Gbit/s using four stages of fibre delay lines. Time delays of more than 1000 bits are inserted at each delay stage to assure data de-correlation between adjacent channels. The OTDM receiver consists of two concatenated EA modulators driven at 10GHz, which produces a switching window of ~5ps. Each EA modulator is integrated with a semiconductor optical amplifier (SOA) to compensate for the loss through the device. A 10GHz sinusoidal RF signal first goes through the digital phase shifter, obtains the desired phase shift and then drives the two EA modulators at the OTDM receiver. In the experiment,  $\tau$  in the digital phase shifter is set to be 10.0ps, which is suitable for operation at 100Gbit/s.



Fig. 2 Traces of sinusoidal RF signal across ten different phase shifts and demultiplexed eye diagrams of ten channels from 100Gbit/s aggregate traffic

*a* Traces of RF signal *b* Demultiplexed eye diagrams 20ps/div

Fig. 2 shows the experimental results of the rapidly reconfigurable demultiplexing among 10 OTDM channels at 100Gbit/s. Fig. 2a shows the traces of the driving sinusoidal RF signal for ten different phases: from phase 1 (10ps) to phase 10 (100ps). After the EA modulators, the demultiplexed eyes from each corresponding phase are measured by a 32GHz photodetector and are shown together in Fig. 2b.

Next we trigger the digital phase shifter with alternating control sequences of [0101] and [0001], resulting in switching between channel 1 and channel 5 at the demultiplexer output. The top trace of Fig. 3 shows the transient response of the sinusoidal RF signal between two different phases. The transition time is 4 ns, including the intrinsic switching of the *pin* diode (~1 ns) and delay in the ECL driver (~3 ns). The demultiplexed eyes during the transition are also shown in the Figure. Although the RF switch does not switch off completely during the transition, the demultiplexed output shows a clean transient response between the two channels due to the high nonlinear response of the EA modulator. As shown on the expanded time scale at the bottom of Fig. 3, switch-off (falling edge) and switch-on (rising edge) of different demultiplexed channels require only 5 and 10 bits at 10Gbit/s, respectively. This indicates the fact that the demultiplexing scheme is able to respond to the RF phase shift at sub-nanosecond speed.



Fig. 3 Transient response of RF switch and EA modulator output and demonstration of fast switching between channels 1 and 5 of demultiplexed output at an expanded time scale

a Transient response of RF switch and EA modulator output

1 ns/divb Fast switching between channels 1 and 5 of demultiplexed output at expanded time scale

200 ps/div

*Conclusion:* In summary, we have demonstrated rapid demultiplexing and tuning of an OTDM channel at an aggregate bit rate of 100Gbit/s based on an RF digital phase shifter. With the nonlinear response in the EA modulators, the scheme only requires a couple of bits at the channel rate in order to reach the steady state. Although our demonstration is achieved at 100Gbit/s, the same device can readily provide fast tuning capability for 16 channels at 160Gbit/s. In conjunction with optical nonlinear devices such as EA modulators, MZ-SOAs and NOLMs, the device can be a potential candidate for a tunable transmitter, receiver, and add-drop demultiplexer in reconfigurable OTDM networks operating at up to hundreds of gigabits per second.

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