

# A 40Gb/s CWDM-TDM PON with a Cyclic CWDM Multiplexer/Demultiplexer

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**Abstract** We demonstrate a 40-Gb/s hybrid CWDM-TDM PON with a novel remote node including a cyclic CWDM multiplexer/demultiplexer. The system uses commercially available 10-Gb/s 1.3- $\mu\text{m}$  directly modulated laser transmitters upstream and 1.5- $\mu\text{m}$  electroabsorption modulated laser transmitters downstream.

## Introduction

Since the first high-volume deployments of time-division multiplexed (TDM) passive optical networks (PON) approximately 10 years ago<sup>1</sup>, the capacities of standardized TDM PONs have steadily increased from 155 Mb/s, to 622 Mb/s, to today's GPON systems<sup>2</sup> with downstream line rates of 2.5 Gb/s. Next generation 10 Gb/s TDM PON standards are under development by both the IEEE and ITU-T.

As line rates increase, satisfying the 28-29 dB power budget requirement (while maintaining low cost) for 20-km, 32-user systems has become increasingly challenging. New 10-Gb/s systems will likely use more costly avalanche photodiode (APD) receivers with forward error correction to make up the additional 6 dB associated with the 4x increase in line rate. Although network operators have no current demand for PON capacities beyond 10 Gb/s, the inexorable progression in core and access network capacities over time makes it imperative that the research community look beyond 10 Gb/s to PONs with total capacities in the 40 Gb/s range.

Given the challenges of producing inexpensive 40 Gb/s transceivers capable of satisfying the 20-km, 1:32 link budget requirement, the singlewavelength per direction TDM PON paradigm is being reconsidered in favor of approaches which utilize WDM. DWDM PONs<sup>3</sup>, which allocate a wavelength per user, or hybrid WDM-TDM PONs<sup>4</sup>, which use several wavelengths at lower line rate while retaining some cost and statistical multiplexing advantages of traditional PONs, have the potential to meet the cost and performance requirements for 40 Gb/s PON.

In this paper, we demonstrate a hybrid CWDM-TDM PON with symmetric 40 Gb/s capacity (4 x 10 Gb/s). A simplified remote node (RN) architecture is enabled by a novel cyclic 1:4 CWDM multiplexer/demultiplexer (mux/dmux).

## Experiment

A schematic of the experiment is shown in Fig. 1. The optical line terminal (OLT) at the central office is connected via 20 km of reduced water peak fiber to a 1:32 RN consisting of a 1:4 cyclic CWDM mux/dmux and four 1:8 passive splitters. The RN connects to 32

user optical network terminals via distribution fibers.

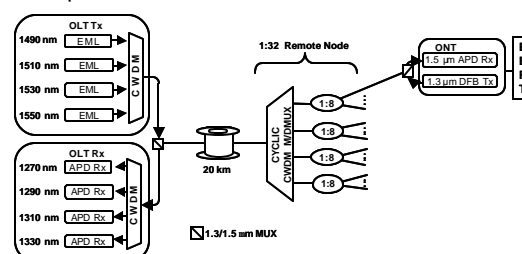


Fig. 1. Experimental setup of the hybrid PON with symmetric 40 Gb/s downstream and upstream capacity.

The cyclic CWDM mux/dmux is a planar lightwave circuit (PLC) in 0.8%-delta silica waveguides on a silicon substrate. The waveguide layout, shown in Fig. 2a., consists of two identical low-order arrayed waveguide gratings (AWGs) connected by equal-length waveguides that perfectly spectrally sample the AWGs. The connecting waveguides are contiguous at one AWG and have gaps between sets at the other AWG<sup>5</sup>. Each AWG has 60 grating arms, and there are 16 connecting waveguides. Because CWDM channels are evenly spaced in wavelength but an AWG is periodic in frequency and because the operating grating orders are very low (8 in the 1500-nm band and 9 in the 1300-nm band), there is significant mismatch between the passband center wavelengths and the CWDM center wavelengths, as can be seen in Figs. 2 (b) and (c). We hope to not only fix this in the future by changing the AWG design, but improve the packaged device loss to less than 2 dB mainly by reducing the fiber-coupling loss.

The transmitters used for the upstream path are directly modulated uncooled DFB lasers with lasing wavelengths of 1270, 1290, 1310 and 1330 nm. The lasers are buried heterostructure designs with InGaAsP multiple quantum wells (MQW) and are optimized for 10.7 Gb/s operation over a temperature range of -5 to +85 °C. The lasers are packaged in an XMD-compatible coaxial TOSA and custom mounted to a high-speed stripline circuit driven directly from the bit error rate tester through commercial bias Ts.

The transmitters used for the downstream path are cooled electroabsorption modulated lasers (EML) with lasing wavelengths of 1490, 1510, 1530 and

1550 nm. The EMLs are fabricated using a butt-joint regrowth process that allows for separate optimization of the InGaAsP MQW DFB laser and InGaAsP MQW modulator. The designs are optimized for 10.7 Gb/s transmission over spans up to 80km and are packaged in an XMD-compatible planar TOSA, which is mounted on a Vitesse EML driver board. All of the transmitters used are commercially available.

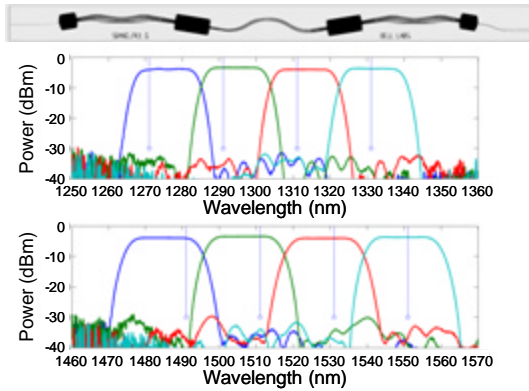


Fig. 2. (a) waveguide layout of the cyclic CWDM multiplexer and (b) and (c) the measured fiber-to-fiber transmissivity vs. wavelength in two different wavelength ranges. The PLC size is  $9.1 \text{ cm} \times 0.5 \text{ cm}$ . The vertical lines in (b) and (c) indicate the CWDM channel location centers.

Both the upstream and downstream transmitters are modulated at 10.7 Gb/s with a  $2^3-1$  PRBS. Each upstream DML launches approximately 2 dBm into fiber, which is then coupled into its distribution fiber with a 1.3/1.5- $\mu\text{m}$  diplexer. After traversing the 1:8 passive combiner, the upstream wavelengths are multiplexed onto the 20-km feeder fiber by the cyclic CWDM mux. An identical diplexer directs the upstream band to a 1.3- $\mu\text{m}$  CWDM dmux at the central office, whose output fibers are connected to the OLT's APD receivers. The downstream EMLs launch approximately 2 dBm into the fiber, are combined by a 1.5- $\mu\text{m}$  CWDM mux at the OLT and then traverse the same path described above in the opposite direction, with the cyclic CWDM at the RN acting as a dmux to direct each wavelength to its

particular 8-user sharing group.

## Results and discussion

Single channel upstream and downstream bit error rate (BER) performance is plotted in Figs. 3a and 3b, respectively. Dark and open symbols represent the back-to-back baseline performance of the commercial APD receiver and the corresponding single channel data through the entire 20-km system. The  $\sim 2$  dB difference in sensitivities between the upstream and downstream data is mostly attributed to the relative power penalties associated with the difference in extinction ratio (ER  $\sim 10$ -11 dB for the EMLs and  $\sim 7.4$  dB for the DMLs, which accounts for 0.8-0.9 dB of relative penalty) as well as  $\sim 0.6$  dB of relative penalty due to the difference in photon energy between 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$ . The simultaneous operation of all 8 wavelengths through the system (Fig. 3c) does not significantly degrade performance. We did not measure upstream performance with a burst-mode receiver, but experimental results from other groups<sup>6</sup> indicate that a high-performance burst-mode receiver would only add one dB of power penalty relative to continuous mode.

In summary, we demonstrated a 40-Gb/s CWDM-TDM PON using a custom cyclic CWDM mux/dmux, taking advantage of the same commercial transceiver technologies currently under development for 10-Gb/s TDM PON. It replaces 6 dB of passive splitting with two stages of CWDM multiplexers. We note that a commercial system based on this design would likely require FEC (as will 10-Gb/s TDM PONs) since the full 28-29 dB power budget required of standardized PON includes several dB of additional margin for splice loss and end-of-life transceiver degradation.

## References

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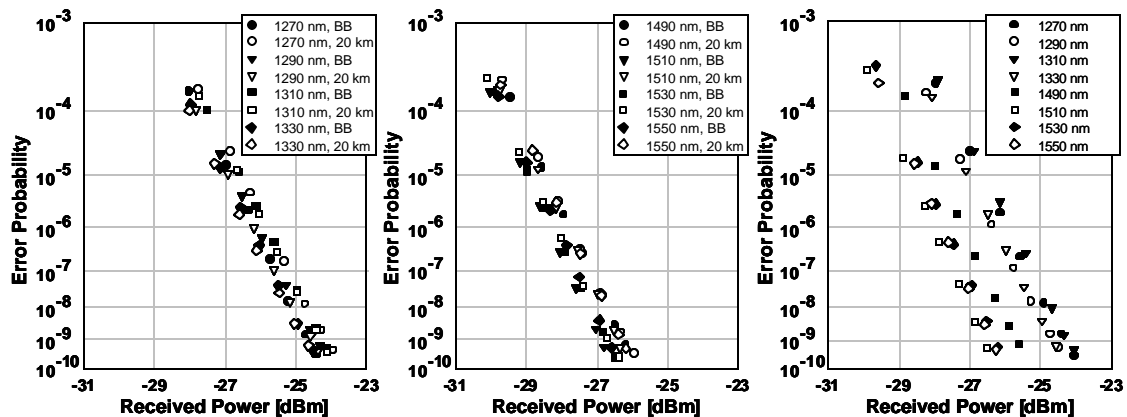


Fig. 3. BER performance for single-channel upstream (a), single-channel downstream (b) and all channels operating simultaneously (c).