Surface Normal Electro-Absorption Modulators as Colorless Upstream Transmitters in a WDM Passive Optical Network

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Abstract: *We demonstrate a WDM passive optical network that uses high-speed, polarization-independent surface normal modulators as upstream 25-Gb/s transmitters. A band of CW wavelengths, sourced at the optical line terminal, establishes the upstream channels. System performance in our single-fiber architecture is limited by Rayleigh backscattering, but is below the FEC threshold.*

1. Introduction

Wavelength-division multiplexed passive optical networks (WDM PON) have been a well-trodden research topic for decades [1], yet the demand for dedicated wavelengths at the network edge is only now materializing. One popular version, the *colorless* WDM PON [2], proposed centrally sourced wavelengths and remote modulation to reduce the costs associated with remote wavelength-specific upstream transmitters. The properties of surface-normal electro-absorption modulators (SNEAM) [3,4], including their high speed, low-cost, and low power consumption, but particularly their polarization-independence and reflective geometry, make them ideal candidates for upstream modulators in colorless WDM PONs. These recent advances in SNEAMs, in conjunction with growing demand for high-speed wavelength connections in mobile radio and data center networks, have motivated this demonstration of upstream transmission in an 8 x 25-Gb/s SNEAM-based WDM PON over distances up to 10 km.

Figure 1 shows the proposed single-fiber colorless WDM PON with the optical line terminal (OLT) on the left and user optical network units (ONUs) on the right. Downstream transmission, shown in red, is straightforward: *N* wavelengths are individually modulated, multiplexed onto a single fiber with a DWDM multiplexer and followed by a diplexer, that adds the modulated downstream and CW upstream wavelength bands. After traversing several kilometers of feeder fiber, the downstream wavelengths are demultiplexed by a cyclic arrayed-waveguide grating (AWG), and directed over relatively short distribution fibers toward *N* ONUs. Each ONU includes a downstream/upstream diplexer, a downstream receiver, and a SNEAM.

Upstream transmission, shown in Fig. 1 in blue, is the focus of this paper. A band of N wavelengths, generated by a comb source collocated with the downstream transmitters, is added to the feeder fiber at the diplexer, traverses the feeder and is demultiplexed by the cyclic AWG onto the distribution fibers. The downstream and upstream wavelength bands are chosen to align with distinct free spectral ranges of the cyclic AWG. At each ONU, an upstream wavelength is directed to a SNEAM, modulated, and reflected back through the system. At the OLT, a circulator directs the upstream wavelength band to a demultiplexer and an array of *N* receivers.

2. Experiment

The experimental configuration, shown in Fig. 2, includes only components for upstream transmission plus all multiplexing stages and the downstream/upstream diplexers. The channel under test is sourced with a DFB laser. After the OLT diplexer, it is combined with seven 25-Gb/s loading channels. The loading channels are generated with a DFB array, whose outputs are combined, modulated with a single lithium niobate (LN) Mach Zehnder modulator, and amplified with an erbium-doped fiber amplifier (EDFA) to overcome the losses of the modulator and passive combiner. These signals, from 1541.6 nm to 1547.4 nm, traverse the circulator and feeder fiber before being demultiplexed by a conventional flat-top AWG with 100-GHz channel spacing. A short distribution fiber connects the AWG output corresponding to the wavelength under test to a diplexer followed by the packaged SNEAM, shown in the inset to Fig. 2. The SNEAM is a modulator that works in reflection [3] and operates under the quantum confined Stark effect. It is composed of a vertical p-i-n stack with an InGaAs/InAlAs multi-quantum-well in its intrinsic region. This structure is inserted in a Fabry-Perot cavity, with a highly-reflective bottom mirror and a partially reflective top mirror. Our device has active area with 20 μm wide diameter and is bonded to a submount with single-ended ground-signal-ground electrodes and an integrated 50 Ohm resistor for impedance matching. The

SNEAM and submount are placed on top of a GPPO connector with wire-bonding between the SNEAM submount and the connector. A standard single mode fiber with a GRIN lens is then glued to the structure and used for both optical input and output. No polarization management components are here used since SNEAMs are fully polarization insensitive. The SNEAM modulates the input CW wavelength with 25-Gb/s baseband NRZ data. The other seven AWG ports are terminated with retro-reflecting mirrors and reflect the modulated loading channels up through the system. After traversing the feeder fiber, a circulator directs the upstream band to an SOA pre-amplified receiver. The SOA amplifies the entire band, thus sharing its cost over all channels. A flat-top AWG demultiplexes the channels and directs the channel under test to a 25-Gbaud receiver consisting of an avalanche photodiode (APD) and trans-impedance amplifier (TIA).

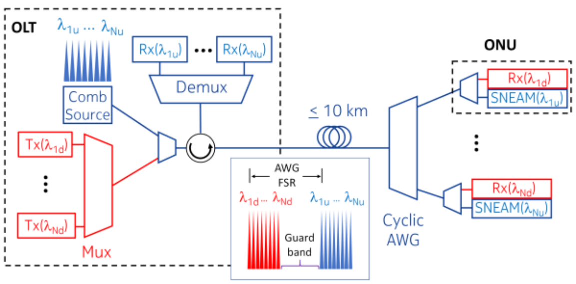

Fig. 1. Single-fiber colorless WDM PON architecture

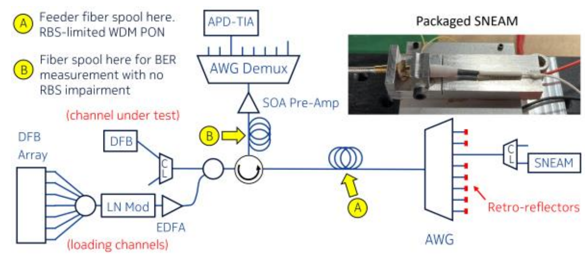

Fig. 2. Experimental set up

Neglecting the loss from the coupler used to add the loading channels, the maximum loss experienced by the wavelength under test was approximately 9 dB from the DFB output to the input to the SNEAM: 1.5 dB from the diplexers and circulator; 5 dB from the AWG; 2 dB from the maximum length of feeder fiber; and 0.5 dB from connectors. Including approximately 3 dB loss from the loading channel coupler, our DFB lasers' maximum launch power of approximately 8 dBm resulted in approximately -4 dBm input to the SNEAM. The SNEAM excess loss of 9.4 dB under NRZ modulation accounts for a power level of -21.5 dBm out of the circulator toward the receiver. The SOA pre-amplifier was necessary to overcome the additional 5 dB loss of the AWG demultiplexer before the receiver.

3. System Performance

The back-to-back, SNEAM-to-unamplified APD-TIA, bit-error-ratio (BER) performance for each wavelength at 25.718 Gb/s NRZ and 2^{31}-1 PRBS is shown in Fig. 3. The solid lines are complimentary error function curve fits. The input power to the SNEAM for all wavelengths was -3.0 dBm and the RF drive voltage was 5.8 V_{pp}. The SNEAM bias voltage was varied from -4.0 V for channel 1 (1541.6 nm) to -4.4 V for channel 8 (1547.4 nm). The extinction ratio for each channel increased from 6.9 dB for channel 1 to 7.5 dB for channel 8. Receiver sensitivities at 10^{-9} BER are within 1.1 dB.

Back-to-back BER performance for the SNEAM-to-preamplified APD TIA, shown in Fig. 4, exhibits greater than 6 dB sensitivity improvement at high BERs (10^{-3} – 10^{-4}) typical of BER thresholds for systems employing forward error correction (FEC).

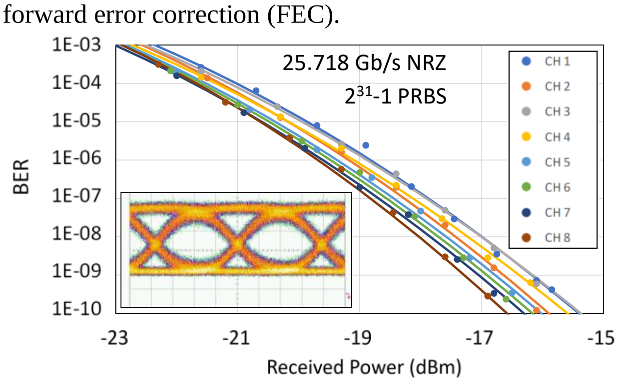

Fig. 3. Back-to-back performance of SNEAM and APD-TIA

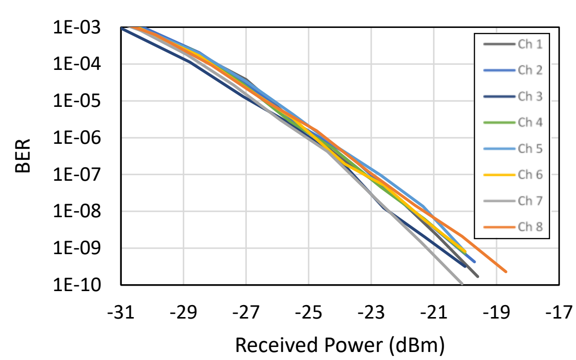

Fig. 4. Experimental set up

In keeping with longstanding practice in PON deployments, our proposed WDM PON architecture features single fiber connections to reduce cost. For conventional baseband NRZ modulation, Rayleigh backscattering (RBS) of the CW wavelength along the feeder fiber adds in-band noise to the upstream signal at the receiver, limiting performance [5]. Since modern PON systems operating at 10 Gb/s and beyond use FEC to reach their target BERs

[6], the BER floors due to RBS can be tolerated over a range of feeder lengths. The effect of RBS for 25-Gb/s NRZ was quantified by comparing channel 8's BER performance for the colorless WDM PON, with an 8-km feeder fiber in location A in Fig. 2, to a more conventional link in which the SNEAM is collocated with the laser source (8-km fiber at B in Fig. 2). These data, along with the back-to-back BER performance for channel 8 are shown in Fig. 5. At a BER of 10^{-3}, conventional transmission through 8 km of standard single-mode fiber adds only a small power penalty relative to back-to-back. Using the SNEAM as a remote modulator, with the 8-km fiber in position A in Fig. 2, causes a significant degradation in performance, although the BER remains below the hard decision (HD) forward error correction (FEC) threshold over the measurement range.

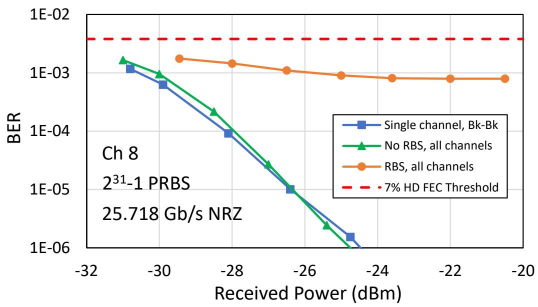

Fig. 5. Effect of RBS on BER for an 8-km feeder fiber

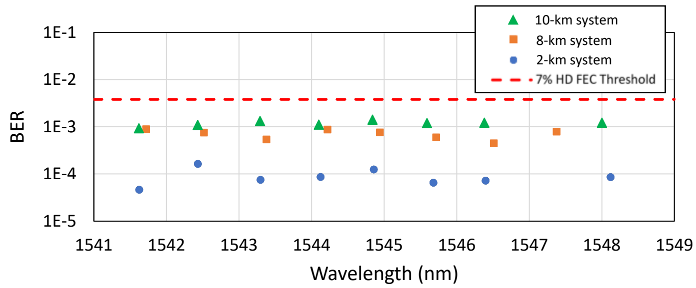

Fig. 6. System performance at 2 km, 8 km, and 10 km

We measured system performance for each channel modulated by the SNEAM, with the others as loading channels. In all cases, the addition of the loading channels did not significantly affect the BER, indicating that the SOA pre-amp was still operating in the linear regime at the maximum total input power to the SOA from all channels of -12 dBm. Fig. 6 shows the BER for each channel with feeder lengths of 2 km, 8 km, and 10 km. All points are below the FEC threshold. Note that for the 2-km and 10-km system measurement the channel-8 DFB stopped working, so we replaced it with a DFB that was aligned with channel 9.

4. Discussion

The impact of RBS on a remotely sourced WDM system such as this is enhanced relative to a simpler single-wavelength point-to-point remotely sourced link, since the loss of the AWG demultiplexer/multiplexer (used to demultiplex the CW source signals and multiplex the returning modulated upstream wavelengths) attenuates the signal twice but does not affect the RBS power generated in the feeder fiber. Thus, the 5-dB excess loss of the AWG that connects the feeder to the distribution fibers decreases the signal to RBS ratio by an additional 10 dB as compared to a point-to-point link. While this version of a SNEAM-based WDM PON uses conventional NRZ modulation for simplicity and is therefore limited to distances less than 10 km, our future work will explore methods for reducing the impact of RBS while maintaining relatively low costs.

5. Conclusion

We have demonstrated a colorless WDM PON that uses low-cost, low power consumption, polarization-independent, reflective SNEAMs as upstream modulators. At distances up to 10 km, BERs for all channels are below the 7% HD FEC threshold.

6. Acknowledgements

We thank Andy Chraplyvy, Bob Tkach, Dora van Veen, Vincent Houtsma, and Mary Phillips for valuable discussions and K. W. Kim for his help mounting the APD receiver.

7. References

[1] For example, S. S. Wagner and H. L. Lemberg, "Technology and system issues for a WDM-based fiber loop architecture", *J. Lightwave Technol.*, vol. 7, pp. 1759-1768, Nov. 1989.
[2] N. J. Frigo, et al., "A wavelength-division multiplexed passive optical network with cost-shared components", *IEEE Photon. Tech. Lett.*, vol. 6, pp. 1365–1367, Nov. 1994.
[3] S. Grillanda, et al., "107 Gb/s ultra-high speed, surface-normal electroabsorption modulator devices," *J. Lightwave Technol*. vol. 38, pp. 804-810, Feb. 2020.
[4] P. Iannone, et al., "PAM-4 transmission up to 160 Gb/s with surface-normal electro-absorption modulators," *Optics Lett*., vol. 45, pp. 4484-4487, Aug. 2020.
[5] T. H. Wood, et al., "Observation of coherent Rayleigh noise in single-source bidirectional optical fiber systems," *J. Lightwave Technol*., vol. 6, pp. 346-352, Feb. 1988.
[6] *10-Gigabit-capable symmetric passive optical network (XGS-PON)*, ITU-T G.9807.1, 2016.