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Beyond 25 Gb/s Directly-Modulated Widely Tunable VCSEL for Next Generation Access Network

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Abstract: We demonstrate capacities beyond 25Gb/s up to 40 km in the whole C-band range without any dispersion compensation by DMT direct modulation and direct detection exploiting widely tuneable MEMS-VCSELs for future low-cost high-capacity access networks.
OCIS codes: (060.2330) Fiber optics communications; (140.7260) Vertical cavity surface emitting lasers; (060.4250) Networks.

1. Introduction

The continuous growth of bandwidth demand in the optical access to support different data traffic including mobile backhaul and fronthaul is pushing the research towards a line rate increase beyond 10 Gb/s. The challenge is to perform this upgrade in a cost-effective way by avoiding expensive premium optical parts [1]. For this reason, in NG-PON2 Full-Service Access Network (FSAN) Group decided to increase the aggregate bitrate using the wavelength dimension in combination with the time dimension, achieving Time and Wavelength Multiplexed-PON (TWDM-PON) [2]. Thus, the next proposals targeting a line rate increase should also be compliant with TWDM-PON standard. In particular, the optical network unit (ONU) transmitters have to be colorless, preferably tunable over 4-8 times the grid-spacing, with very high side-mode suppression (SMSR) to avoid crosstalk into neighboring channels. Moreover, in addition to these stringent requirements for transmitters, to keep the cost low, direct-detection receivers using limited bandwidth optical components should be used to enable 25G and 40G PONs.

In this paper, we present for the first time the exploitation of a long-wavelength widely tunable vertical-cavity surface-emitting laser (VCSEL) [3] to achieve a colorless ONU transmitter, presenting low-cost and reduced footprint. Discrete multitone modulation (DMT) combined with direct detection (DD) is employed to use limited-bandwidth VCSELs and standard receivers suitable for 10 Gb/s operation, targeting a transported upstream (US) capacity greater than 25 Gb/s up to 40-km standard single-mode fiber (SSMF) without any chromatic dispersion (CD) compensation. Transmission up to 20-km SSMF is demonstrated in the NGPON2 US band, while the whole C-band coverage and 40-km SSMF reach are obtained thanks to asymmetrical filtering of the received signals at the central office (CO).

2. Directly modulated tunable VCSEL

The employed single-mode widely tunable long-wavelength VCSEL is based on a long wavelength Indium Phosphide (InP) Buried Tunnel Junction (BTJ) VCSEL and features a MEMS top mirror [4]. The small air gap between the surface of the base VCSEL and the MEMS can be thermo-electrically controlled. The change in air gap leads to mode-hop free tuning of the laser wavelength of about 90 nm (from 1517 nm to 1608 nm), showing a SMSR above 45 dB on the entire tuning range. The peak optical fiber-coupled power is 1.2 mW at 22°C with a bias current of 32 mA. The VCSEL has a maximum S-21 3-dB bandwidth of about 7 GHz at 1550 nm, while on a 47-nm wavelength range a minimum bandwidth of 4.5 GHz is guaranteed [5]. Recently, 10-Gb/s directly-modulated non-return-to-zero (NRZ) transmission has been demonstrated for a compensated 40-km SSMF span [6].

The employed VCSEL is packaged in a transmitter optical subassembly (TOSA) with standard LC connector. Inside the TOSA package a thermoelectric cooler, a thermistor and a monitoring diode have been included. Only one control signal is required to tune the laser without mode hops across the full tuning range. In total, only 8 pins are required for the described functionality. Moreover, the exploited device can be assembled inside standardized small form factor pluggable (SFP) optical modules.

3. Experimental setup

For the US transmission performance evaluation, we employed the experimental setup shown in Fig. 1. The ONU VCSEL is directly modulated by a DMT signal generated by a Tektronix 50 GS/s arbitrary-waveform-generator (AWG 70001A) with 14-GHz electrical bandwidth. The DMT signal is calculated by Matlab® and is composed by 255 sub-carriers in 8 GHz range, i.e. the sub-carrier spacing is 31.25 MHz. A cyclic prefix (CP) of about 2.1% of the symbol length is added. The bias current and modulation amplitude are maintained constant at 16 mA and 950 mV, respectively, for the entire C-band wavelength tuning range.

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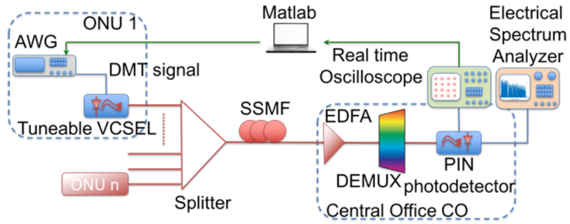

Fig. 1. Experimental setup.

The DMT signal is transmitted over up to 40-km uncompensated SSMF. At the receiver end, a low-noise Erbium-doped fiber (EDF) preamplifier and a variable optical attenuator (VOA) anticipate a WDM demultiplexer followed by a standard PIN receiver suitable for 10 Gb/s operation. The received signal is acquired by a Tektronix real-time oscilloscope (DPO 73304DX) with 8 bits vertical resolution, 50 GS/s and 33-GHz electrical bandwidth while off-line processing provides digital symbol synchronization, CP removal, sub-carriers phase recovery and demodulation. The presence at the CO of an EDF preamplifier shared between all the subscribers is compliant with the NGPON2 architecture, nevertheless, the employment of a 10-Gb/s avalanche photodiode (APD) receiver would allow to avoid the EDF amplifier presence. To cope with the CD accumulated over SSMF propagation distances up to 40 km, we also evaluated the impact of asymmetrical filtering [7], provided by the WDM demultiplexer on the DMT transmission performance. Specifically, in our setup a 0.3-nm tunable optical filter mimics the CO demultiplexer and is fine-tuned with respect to VCSEL emission wavelength thanks to the exploitation of an electrical spectrum analyzer. Performance evaluation is provided comparing results achieved with the filter centered at the VCSEL emission wavelength and with 5 GHz detuning.

4. Experimental results and discussion

At first the estimation of the US channel characteristics has been performed by transmitting a probe DMT signal mapped with uniform QPSK loading after direct detection, providing the signal-to-noise ratio (SNR) of each sub-carrier. An example of measured SNRs in case of back-to-back (BTB) condition, 40-km SSMF propagation with centered filter and 40-km SSMF propagation with detuned filter is shown in Fig. 2(a) at 1535 nm. After 40 km of SSMF propagation (red curve), the cumulated chromatic dispersion leads to an evident frequency dip around 5 GHz, where the corresponding SNR shows a minimum of about 4 dB. Thanks to the filter detuning (green curve), the impact of chromatic dispersion is mitigated leading to an almost unchanged SNR response with respect to the BTB condition.

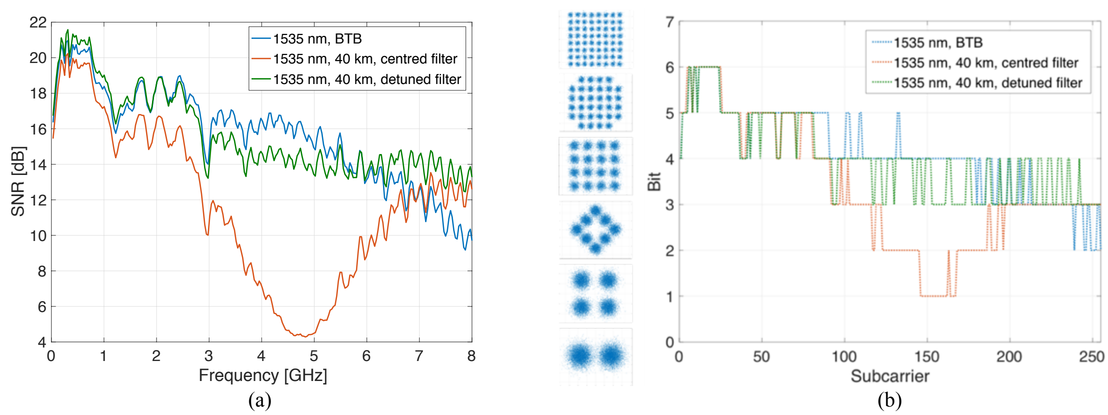

Fig. 2. (a) Measured SNRs at 1535 nm and (b) corresponding bit mapping of the 255 sub-carriers for back-to-back condition (blue curve), after 40-km SSMF propagation with centered filter (red curve) and detuned filter (green curve). Examples of the received constellations are shown on the left inset of (b).

The measured SNRs are exploited for performing Chow's algorithm, which is a relatively simple bit- and power-loading procedure for obtaining a good approximation of the highest bit rate achievable by the transmission system [8], setting the target bit error rate (BER) at $3.8{\cdot}10^{-3}$ (useful for exploiting an advanced hard-decision forward error correction code with 7% overhead). The obtained bits per symbol distribution among the different sub-carriers is reported in Fig. 2(b); in the left side inset, examples of the corresponding received constellations are also displayed.

As expected, a clear improvement of the total capacity transmitted after 40 km of SSMF is obtained by the detuning of the optical filter, which permits to exploit a bit mapping among the sub-carriers similar to the BTB

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condition. On the other hand, when the centered filter is exploited, only modulations with lower orders can be achieved, in particular, around the frequency dip at 5 GHz, leading to a reduction in the total transported capacity.

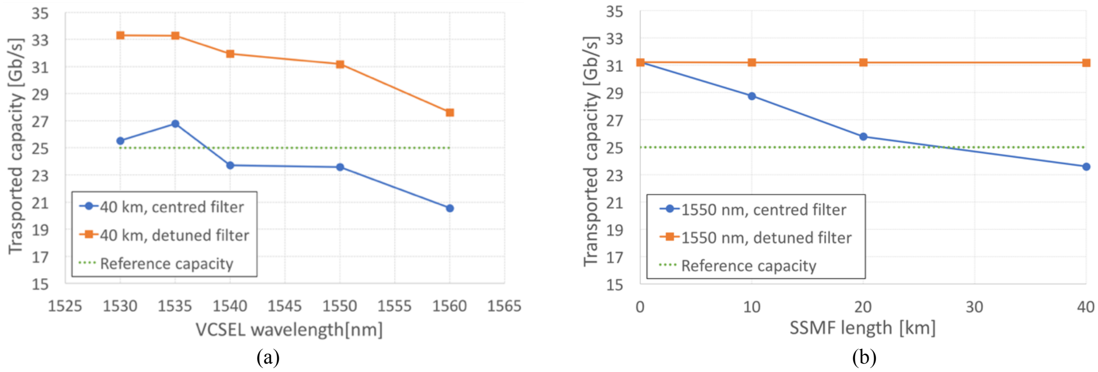

Fig. 3. (a) Total capacity transported by the system with centered (blue line, circles) and detuned (orange line, squares) filter. (b) Total capacity transported at 1550 nm vs propagation length in case of centered filter (blue line, circles) and detuned filter (orange line, squares). The reference capacity of 25 Gb/s is the green dotted line.

In Fig. 3(a) the total capacity achievable in case of centered (blue line) and detuned (red line) filter is shown for -6 dBm received optical power, while the green dotted line represents the reference capacity of 25 Gb/s. In case of filter detuning, in the entire C-band US capacity higher than 27 Gb/s are achieved. Since the bias current and the modulation amplitude of the RF drive signal optimized for 1535 nm are not changed in the test of the whole C-band, a reduction in the transported capacity is noticeable at higher wavelengths, where a different optimization should be performed. On the other hand, when the filter is centered to the VCSEL emission, the transported capacity varies between 27 Gb/s at 1535 nm and 20 Gb/s at 1560 nm. Then, the total capacity achievable as function of the SSMF propagation length has been experimentally evaluated. Fig. 3(b) shows the results for 1550 nm in case of centered (blue line) and detuned (red line) filter with respect to the reference capacity of 25 Gb/s (green dotted line). As expected, when the filter is detuned no reduction of the capacity depending on the SSMF length is noticeable, confirming bit-rates higher than 25 Gb/s up to 40 km. On the other hand, when the filter is centered, 25-Gb/s capacity is achieved up to 20-km SSMF propagation, which is the minimum reach requested by 10-Gb/s PONs. In particular, this result is demonstrated for all the wavelengths under 1550 nm.

5. Conclusions

DMT US transmission beyond 25 Gb/s has been shown by exploiting a widely tunable VCSEL operating over the whole C-band. Uncompensated 20-km SSMF reach is achieved, demonstrating 25-Gb/s capacity in the NGPON2 US band. 40-km SSMF reach can be also obtained thanks to the support of asymmetric filtering. The employment of the experimented tunable VCSEL combined to DMT direct modulation and DD appears as a very promising solution to realized high-bandwidth TWDM PON with low-cost, reduced footprint ONU sources, targeting at least 25 Gb/s capacity while exploiting devices suitable for 10 Gb/s operation.

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