# Full C-band Tunable MEMS-VCSEL for Mobile Front- and Backhaul

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## Summary / Abstract

In this paper we report on full C-band tunable, 10 Gbit/s capability, directly modulated micro-electromechanical system (MEMS) vertical-cavity surface-emitting laser (VCSEL) for next generation converged mobile fronthaul and backhaul applications, where the MEMS-VCSEL is used at the remote side of a wavelength routed WDM-PON system. To be compliant with the current ITU-T G.metro standardization, we also evaluate the transmission performance with the out-of-band pilot tone modulation. The results show that bit error rates below $10^{-9}$ were achieved over up to 30 km SSMF, both without and with the imprinted pilot tone, while the power penalty provoked by this pilot tone was less than 1.4 dB within 20 km transmission distance.

## 1 Introduction

The tremendous increase of mobile traffic demands is imposing an imminent reformation on the radio access network (RAN) infrastructure [1]. It can be foreseen that most radio signal processing in the baseband unit (BBU) will be centralized, in order to ease the implementation of the advanced 5G radio access technologies (RATs). Moreover, since the remote radio head (RRH) only performs the RF-band/baseband conversion, the CAPEX and OPEX can be reduced. However, this split results in stringent bandwidth and latency requirements on the mobile front-haul (MFH), which is the transport link between BBUs and RRHs [2]. A cost-efficient solution to the MFH is the wavelength division multiplex (WDM) passive optical network (PON), which provides the optical fronthaul between the RRH at the antenna tower and the BBU at the central office (CO). On the other hand, to bring down the overall cost and improve the operational efficiency, a centralized wavelength locker is introduced at the optical line terminal (OLT) to enable the autonomous wavelength tuning of the tunable laser in the optical network unit (ONU) [3]. Currently, the ITU-T Study Group 15, Question 6 (Q.6/15) is drafting a new recommendation G.metro, proposing the next-generation WDM access facilitated by such a wavelength-agnostic concept. A communication channel between the OLT and ONUs is also being defined as an auxiliary management and communication channel (AMCC) in the G.metro draft. We will use the Q.6/15 terms in the rest of this paper, i.e. the head-end equipment (HEE) and the tail-end equipment (TEE) denote OLT and ONU, respectively.

However, the biggest challenge up to now is the lack of low-cost wideband tunable lasers for 10G transmission. Therefore, we believe and propose that micro-electro-mechanical systems (MEMS) vertical surface emitting laser (VCSEL) is very promising for the low-cost, 10 Gbit/s transmission over at least 20 km, as well as offering simplicity for wideband autonomous tuning. A distinct pilot tone can be imprinted on the payload of each uplink wavelength, and the centralized wavelength locker will then calculate all the feedback pilot tones for the wavelength deviation [4].

In this paper, we present a WDM-PON transmission based on a wideband tunable MEMS-VCSEL, operating at 10 Gbit/s over up to 40 km. Details of the packaged MEMS-VCSEL are also presented. Furthermore, we also analyze for the first time the impairment on the uplink payload caused by the pilot tone. Results show that MEMS-VCSEL based WDM-PON is a viable solution to coping with the pressing MFH needs.

## 2 Wavelength-agnostic WDM-PON

As already mentioned, a key element of the wavelength-agnostic WDM-PON is the wideband tunable laser in the TEE. The laser should be (at least) capable of a tuning range of the C-band and the capability of 10 Gbit/s transmission over 20 km. To achieve the lowest cost of the laser, the dedicated wavelength locker in each laser module can be replaced by the centralized wavelength locker at the HEE, and also the calibration on a per-sample base can be avoided.

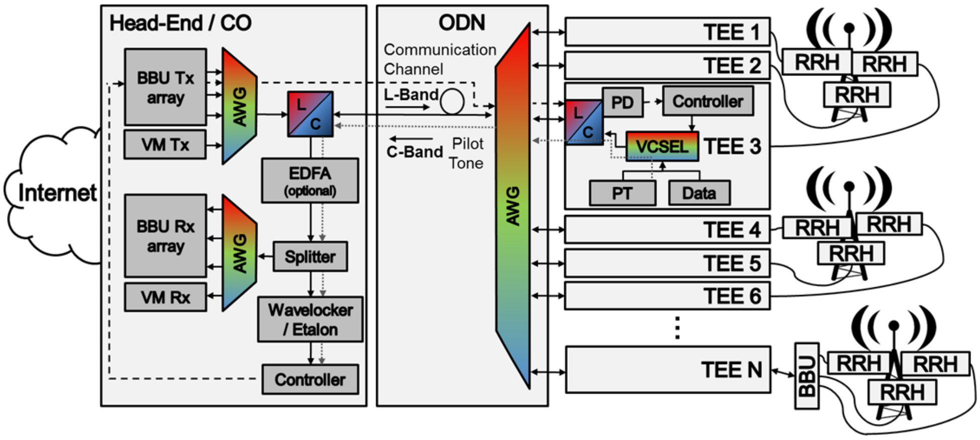


**Figure 1** System concept for converged mobile MFH and MBH. BBU: Base Band Unit; VM: Virtual Machine; TEE: Tail-End Equipment; PT: Pilot Tone; RRH: Radio Remote Head

The WDM-PON concept is shown in **Figure 1**. It features autonomous wavelength tuning using a centralized wavelength locker. This centralized locker is shared by all TEEs [5].

It is also worth pointing out that the WDM-PON can be in principle used not only for fronthaul but also for backhaul applications. MFH is mostly based on the Common Public Radio Interface (CPRI) protocol, while mobile backhaul (MBH) uses the Ethernet protocol. Thus, both applications can benefit from the transparency of the system [6].

The optical distribution network (ODN) can be based on a tree or dropline architecture. The wavelength multiplexing (MUX) and de-MUX in the tree architecture are based on arrayed waveguide gratings (AWG). If the feeder fiber is much longer than the drop fibers, the differential end-to-end reach in most cases is small, e.g., <5 km. Then, a single dispersion compensating fiber (DCF) in the head-end allows optimization of the chromatic dispersion (CD) for all channels. Droplines, on the other hand, use optical add/drop multiplexers in several locations. Now, the differential reach can be as long as the system specifications, i.e., 20 km for MFH. Since both architectures need to be supported, this results in the requirement for a single DCF, which needs optimization over the complete range of relevant reach.

## 3 Tunable MEMS-VCSEL

The transmission experiment is based on a single-mode widely tunable 1.55 µm VCSEL. It has been packaged as a transmitter optical subassembly with a standard LC connector (LC TOSA, **Figure 2**) and can be assembled inside standardized small form factor pluggable (SFP) optical modules. The tunable laser diode is based on a long wavelength Indium Phosphide (InP) Buried Tunnel Junction (BTJ) VCSEL and features a MEMS top mirror. A cross section of this VCSEL design is illustrated in **Figure 3**. Details about the device structure and manufacturing can be found in [7-9].

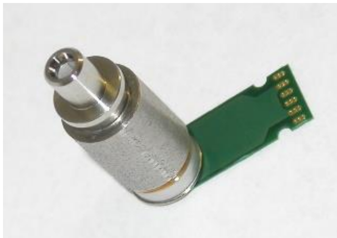

**Figure 2** Photo of packaged LC-TOSA

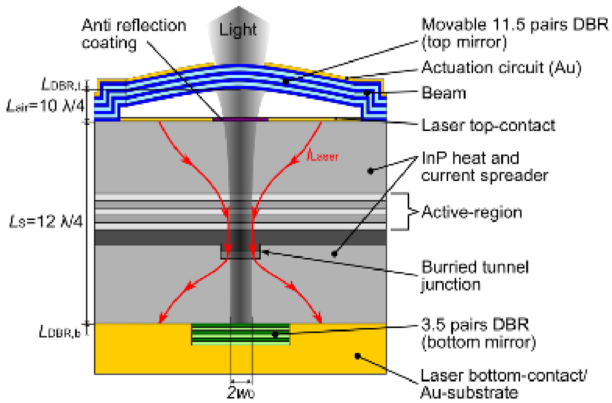


**Figure 3** Cross section description of MEMS-VCSEL

The small air gap between the surface of the base VCSEL and the MEMS can be controlled thermo-electrically. The change in air gap leads to mode-hop free tuning of the laser wavelength. The tunable VCSEL deployed for this experiment has a maximum tuning range from 1517 nm to 1608 nm (**Figure 4**) and a peak optical power of 1.2 mW (fiber coupled). For the transmission tests, the tuning range was limited from 1530 nm to 1592 nm to compensate a decrease of the optical power at the boundaries of the tuning range. In the future, the design will be optimized to enable the use for both C- and L-band applications with one laser.

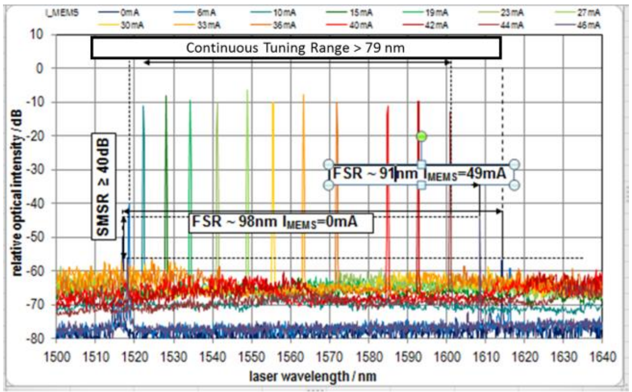


**Figure 4** Tuning range of MEMS-VCSEL

Several components and functions are integrated inside a small TO-46 based LC TOSA package. These include a thermoelectric cooler, a thermistor and a monitoring diode. 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.

# 4 Experiment setup and results

In the experiments, we focused on the upstream application for MFH and MBH, therefore, with a limited reach of up to 40 km. **Figure 5** shows the experimental setup. A bit error rate tester (BERT) generated a $2^{31}$-1 bit long pseudo-random bit stream (PRBS 31) at 10.3125 Gbit/s, while a 50 kHz sinusoidal pilot tone was generated by a FPGA board with a modulation index of 10%. Both the data signal and the pilot tone were combined and directly modulated on the MEMS-VCSEL bias current. The bias current and modulation amplitude was kept constant for all measurements at 22 mA and 1 V, respectively. The signal was launched into a standard single mode fiber (SSMF) via an AWG used as multiplexer and was transmitted over up to 40 km. At the head-end, the dispersion was compensated by a DCF matched to 40 km SSMF for all transmission lengths. The G.metro standard considers an optional Erbium-doped fiber amplifier (EDFA) in upstream direction to ease the link budget on the tail-end tunable transmitter. The cost of EDFA and DCF can be shared among all subscribers, and therefore, still supports the low cost approach. The dispersion compensated and amplified signal was de-multiplexed by an AWG and finally launched into an SFP receiver on an evaluation board via a variable optical attenuator (VOA). The opto-electrically converted signal was connected back to the BERT to evaluate the BER.

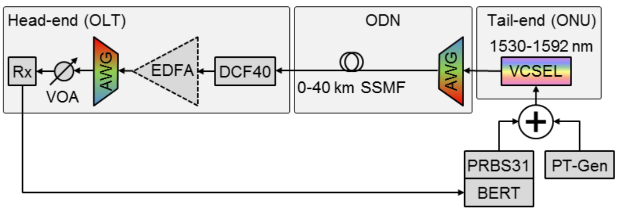


**Figure 5** Experimental setup applying MEMS-VCSEL

**Figure 6** shows the BER without fiber transmission as a function of the received power in two cases, i.e. with or without pilot tone modulation. It can be seen that the receiving sensitivity across the available C-band channels (1530 nm to 1561 nm) is consistent. When the pilot tone is transmitted, the receiving sensitivity is slightly deteriorated by about 1 dB at the BER of $10^{-9}$.

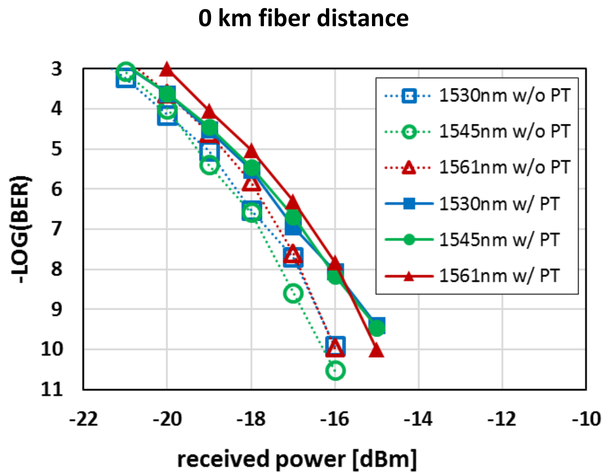


**Figure 6** "zero-km" BER performance of different wavelengths with and without the pilot tone

Then we included a fiber spool in the setup to evaluate the transmission performance. **Figure 7** shows the result of the same BER measurement after 20 km fiber transmission. Since the DCF compensated the chirp of the VCSEL laser, no impairment was observed after the transmission. We also measured the performance with 10 km fiber, which gave a similar result.

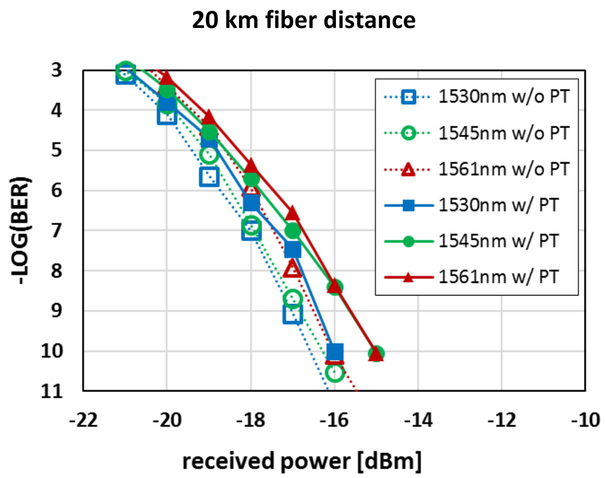


**Figure 7** BER performance with and without the pilot tone after 20 km fiber transmission

**Figure 8** shows the transmission results for SSMF transmission over 0-30 km plus a constant DCF matched to 40 km (transmission length of 0 km means that the signal was launched directly into the DCF after the first AWG). For a BER of $10^{-9}$, the receiver sensitivities after 20 km SSMF transmission are similar to the zero-km case. For transmission lengths between 0 km and 20 km, the receiver sensitivity varies less than 1 dB in all the scenarios. We believe that the slightly better receiving sensitivity with the 20 km fiber is due to the chirp of the laser. Within 20 km transmission range, we can conclude that the power penalty provoked by the pilot tone is between 0.5 to 1.4 dB for all the wavelengths.

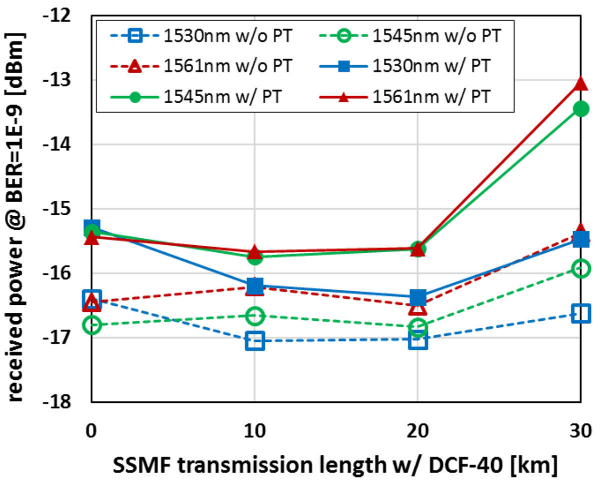


**Figure 8** Comparison of receiving sensitivity as a function of SSMF transmission length plus DCF

For G.metro MFH applications, the total reach is specified up to 20 km, mainly because of the stringent latency requirement (e.g. by CPRI). From **Figure 8**, it can be seen that the receiver sensitivity varies within 1 dB over the entire C-band range. On the other hand, the additional power penalty due to the imprinted pilot tone varies within 1.4 dB. This should be sufficient for the system implementation, given that the laser settings are kept the same for all wavelengths and transmission lengths without individual optimization. For other applications like the MBH and enterprise access, however, the penalty might be slightly increased as they usually require a longer differential reach.

# 5 Conclusions

Up to now, low cost wideband tunable laser sources are the bottleneck of the G.metro system, and therefore, the concept was not competitive enough for wide deployment. This paper provides the experimental demonstration of a system based on tunable MEMS-VCSELs which overcome this bottleneck. We demonstrated the error free transmission of 10 Gbit/s direct modulation over 30 km SSMF for the tuning range of more than 60 nm. The possible impairment of the imprinted pilot tone was also analyzed in the experiment. The results proved that this laser is more than suitable for the proposed MFH and MBH network application utilizing the novel G.metro WDM-PON system.

# 6 Acknowledgements


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# 7 Literature


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