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Electro-absorption modulated laser for analog and digital satellite payload applications

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ABSTRACT

Optical technologies play an increasing role in telecom satellite payloads for analog or digital applications. When large SWaP (size, weight, and power) is prohibitive or for applications where low cost is a major design goal, an electro-absorption modulated laser (EML) can provide a good balance between integration and performance optimization through separated control of emission and modulation. 1550 nm EML for ground applications were evaluated for optical local oscillator (LO) distribution, photonic RF frequency conversion, digital and analog free-space optical (FSO) communications.

An EML-based LO distribution was assessed in terms of RF output power, spectral purity and phase noise. Using optical amplification, large-scale distribution of a 13 GHz LO was achieved with similar or greater RF power and a limited noise floor penalty compared to what is possible with a CW laser and Mach-Zehnder modulator (MZM). Photonic RF frequency-conversion was assessed as well and EML was found to perform better than direct modulation laser.

For optical inter-satellite links in constellations, SWAP and cost really matter and EML is therefore an interesting candidate. An EML-based transmitter was evaluated for digital modulation at 10 and 20 Gbps as well as for RF analog modulation in transmit Ka band (20 GHz). For digital modulation, an EML module exhibited a similar dynamic extinction ratio as a MZM, and a limited penalty in detection sensitivity. For RF modulation, the carrier-to-noise ratio was measured as a function of the received optical power for various EML operating conditions: equivalent RF performance were achieved as well.

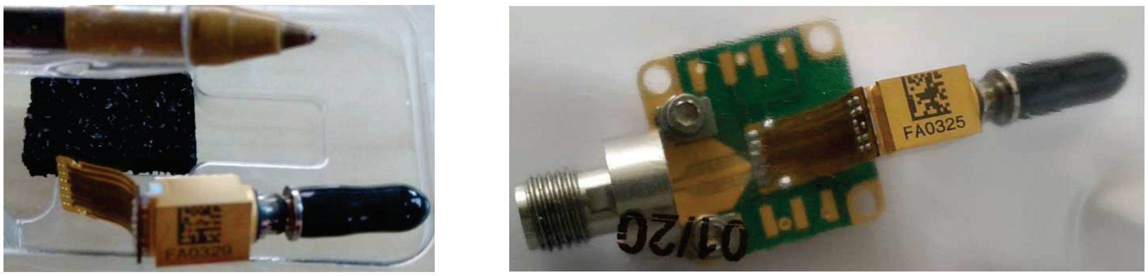
Keywords: Electro-absorption modulated laser, local oscillator distribution, photonic RF frequency conversion, digital and analog free-space optical communications

1. INTRODUCTION

Optical technologies are to be increasingly embarked on board of telecom satellite payloads for analog or digital applications. For single-mode operation with bandwidth greater than 10 GHz, the straightforward approach for the emission is to use a CW laser and a Mach-Zehnder electro-optical intensity modulator (MZM). The separation of optical carrier generation and RF modulation allows the transmitter performance to be optimized in terms of bandwidth, noise and extinction ratio compared to the directly modulated laser. Nevertheless, its SWaP (size, weight and power) and cost can be prohibitive for large-scale implementations or applications where low cost is a major design factor. The electro-absorption modulated (EML) laser can provide a good compromise offering the SWaP and cost of directly modulated lasers, as well as the potential for performance optimization through separation of carrier generation and modulation. 10G and 25G 1550 nm EML COTS developed for terrestrial applications were evaluated in the following space applications: optical local oscillator (LO) distribution, photonic RF frequency conversion, digital and analog free-space optical (FSO) communications.

2. EML DESCRIPTION

C-band 10G EML from Sumitomo Electronic (ELD5403QK) and 25G EML from Almae Technologies (CET8-25) were purchased. In sections 2 and 3 is presented only the EML from Almae Technologies. This EML was designed for 10 km terrestrial applications at 25 Gb/s. The chip includes monolithically a DFB laser diode and an electro-absorption modulator. The chip is assembled with a thermistor, a TEC and an optical isolator into a TOSA package with FPC flex. The size of the TOSA body is as small as 12.9 x 5.4 x 5.5 mm and the mass is only 2 g. The EML chip was designed for chip set temperature from 35 to 50°C in order to reduce the consumption for hot case temperature. A picture of the TOSA module and its mounting onto a test-board PCB which includes a 50 Ω line and a 2.92 mm RF connector is shown in Fig.1.

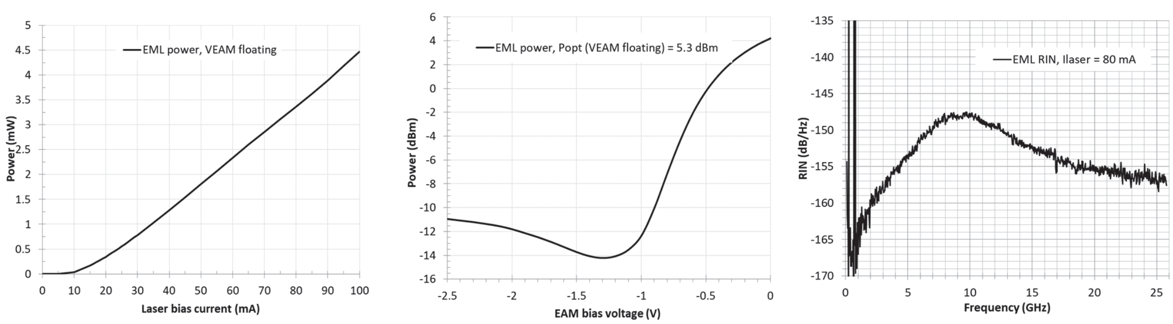


(a) (b)

Figure 1. (a) EML sample to be evaluated, (b) EML mounted onto a PCB for testing

3. EML CHARACTERIZATION

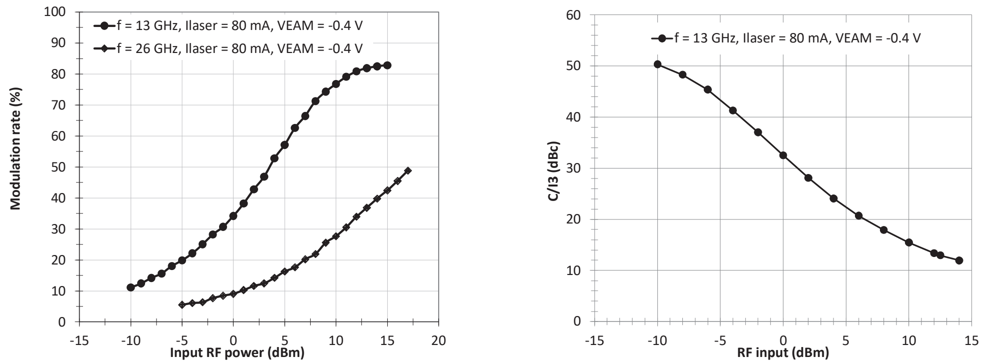
EML was first characterized at ambient temperature with chip set temperature at 45°C. Fig. 2 (a) shows the power as a function of laser bias current. The electro-absorption modulator (EAM) was not biased (floating voltage). The threshold current is about 10 mA and the fibered output power is 4.5 mW (+6.5 dBm) at 100 mA laser bias current. The power as a function of EAM bias voltage is plotted in Fig. 2 (b). The laser is set at 80 mA which correspond to an output power of 5.3 dBm when the EAM is not biased. The static extinction is superior to 18 dB and the minimum power is obtained for V_{EAM} = -1.25 V. The SMSR (side mode suppression ratio) is higher than 50 dB.The relative intensity noise (RIN) was also measured from 0.08 to 26 GHz. As shown in Fig. 2 (c), the RIN does not exceed -147 dB/Hz.



(a) P-I (b) P-V (c) RIN

Figure 2. EML characteristics at room temperature (chip set @45°C)

As such EML were considered to be used potentially for optical distribution of RF local oscillators and for transmission of analog RF signals as well, we also measured the EML modulation ratio and 3rd-order linearity. Fig. 3 (a) and (b) hereafter respectively show the modulation ratio at 13 and 26 GHz, which corresponds to typical LO frequencies before and after doubling, and the C/I_3 (carrier-to-3rd-order-intermode) ratio against the RF input power, which is the conventional and key linearity performance indicator. At 13 GHz, the modulation ratio goes up and saturates around 80 % from 10 dBm RF input power. At 26 GHz, the modulation is limited to less than 50 %. It also turns out that C/I_3 ratios higher than 40 dB can be achieved provided that the RF input power is below -3.5 dBm. This corresponds to a 3rd-order intercept point of +16.5 dBm.



(a) Modulation rate at 13 and 26 GHz

(b) Third-order intermodulation ratio at 13 GHz

Figure 3. EML RF-characteristics at room temperature (chip set @45°C)

4. OPTICAL LOCAL OSCILLATOR DISTRIBUTION

Local oscillator distribution is a key function inside telecom payloads for frequency up- and down-conversions [1-3]. Optical LO distribution was evaluated at 13 and 26 GHz which correspond to the LO typically required to Ka/C frequency converters either for direct use or for multiplication by 2 before mixing. An optical LO distribution tesb-bed was assembled at Thales Alenia Space. The performance of optical LO distribution using an EML as photonic LO transmitter was assessed in terms of RF output power, spectral purity and phase noise, with and without optical amplification.

The optical LO distribution architecture considered using the Almae Technologies EML is shown in Fig. 4 below. An optical fiber amplifier (OFA) can be inserted after the transmitter in order to boost the optical power (passive or active architecture). Optical splitting losses due to the distribution rank were emulated by using a VOA (variable optical attenuator), each division by 2 being emulated by 3.5 dB loss. The O/E conversion is done by a commercial high-speed photodiode.

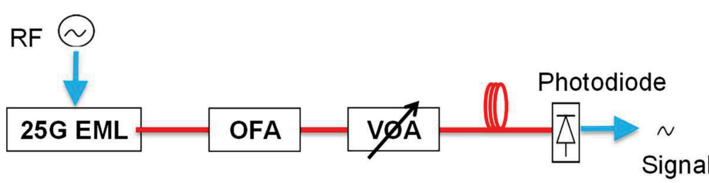
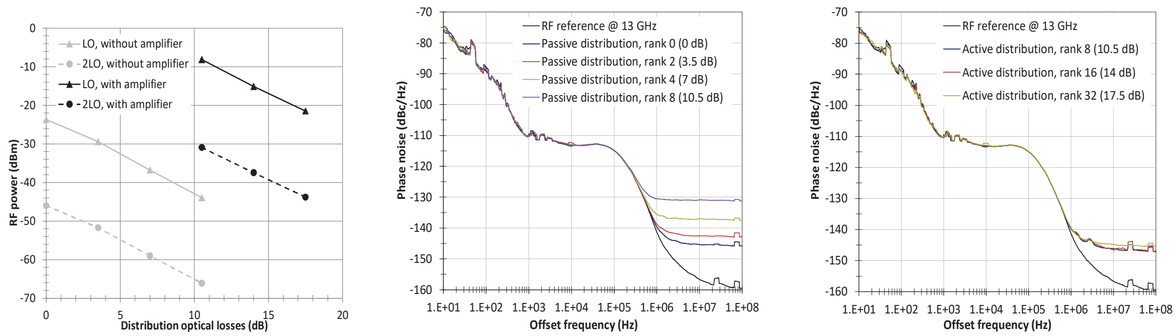


Figure 4. Schematic of the optical LO distribution set-up

Without optical amplification, the performances are quite poor as shown in Fig. 5(a) and (b). Noise floor is about -146 dBc/Hz for rank 0 but it rapidly increases to -131.3 dBc/Hz for rank 8 which is more than 10 dB above our needs. LO power is also limited: for rank 8 the LO power is -43.9 dBm. This level is too low to be compensated by RF amplification. Up to now, there is no targeted application for this configuration (no optical amplification).

The second LO distribution architecture includes a 19.4 dBm output power optical amplifier. The results obtained are very attractive: for a distribution rank of 32 (17.5 dB loss) at 13 GHz, the optical link noise floor is -145.5 dBc/Hz and the LO power is -21.5 dBm, as shown in Fig. 5 (a) and (c). A one-stage RF amplifier will allow to reach about 0 dBm RF power which is a sufficient level for this application. These results are obtained with an input electrical LO power of only 10 dBm.

By increasing this value, for example to 13 dBm, we will be able to increase the modulation rate from 77 to 82 % and so to increase slightly the performances.
The EML laser bias has not significant impact on the LO distribution performances. On the contrary the EAM bias tuning can improve the noise level to few dB at the price of the degradation of the spectral purity (increase of 2OL signal) due to EAM non-linearity.



(a) RF output power for passive/active LO distribution at 13 GHz

(b) Phase noise for passive LO distribution at 13 GHz

(c) Phase noise for active LO distribution at 13 GHz

Figure 5. RF performance of optical LO distribution at 13 GHz

In order to benchmark the performance of the EML, we simulated with an homemade software the performance of an LO distribution sub-system using a high-power low-noise CW laser and a MZM external modulator. The results are compared in Fig. 6. The EML noise floor penalty at 10 MHz offset frequency is 2.8 dB if we consider a MZM with a modulation rate of 1. With a modulation rate of 0.77 (EML measured value), the penalty decreases to 1.5 dB. This penalty is surely due to the RIN level difference between the EML and high power CW laser (-148 dB/Hz vs -165 dB/Hz).

At 26 GHz the distribution of optical LO works properly up to rank 32 (maximum rank tested) when the input LO power is increased to +17 dBm (see Fig. 7). In this case, the EML is used far away from its -3 dB bandwidth. The -3 dB bandwidth could be increased by improved the EML RF access.

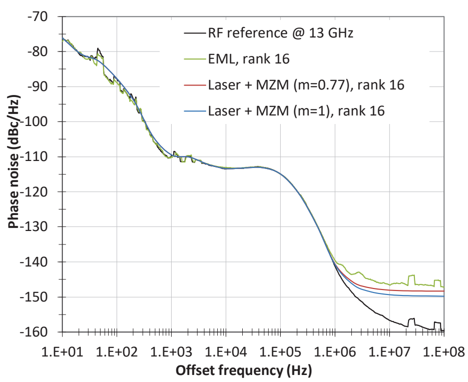


Figure 6. RF phase noise of Active LO distribution at 13 GHz for an EML (measurement) and Laser + MZM (simulations)

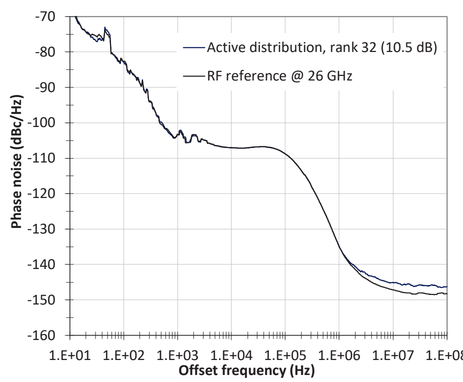


Figure 7. RF phase noise for active EML-based LO distribution at 26 GHz

Attractive LO distribution performance at 13 and 26 GHz were measured using the EML-based active architecture. Compared with a reference MZM, the phase noise floor penalty is limited to a few dB even at large distribution rank.

5. PHOTONIC RF FREQUENCY CONVERSION

EML devices have also been assessed for application in photonic RF frequency-conversion sub-systems. In the reference architecture shown in Fig. 8, the RF signal to be frequency-translated needs to be transferred onto an optical carrier through a photonic RF transmitter and be assigned a specific wavelength. The photonic RF signal is then supplied to the optical input of an electro-optical mixer, e.g. a MZM, the electrical RF port of which is driven by the RF LO. An optical band-pass filter (or a WDM) is used at the output to remove optical noise before O/E detection that converts the optical signal back into an RF signal at the intermediate frequency. Optical amplifiers are there either at the input or the output of the mixer or at both, in order to improve the RF conversion gain and noise figure performance. More advanced configurations taking benefit from WDM to implement multiple channels and support simultaneously multiple frequency-conversions, are possible and described for instance in [4].

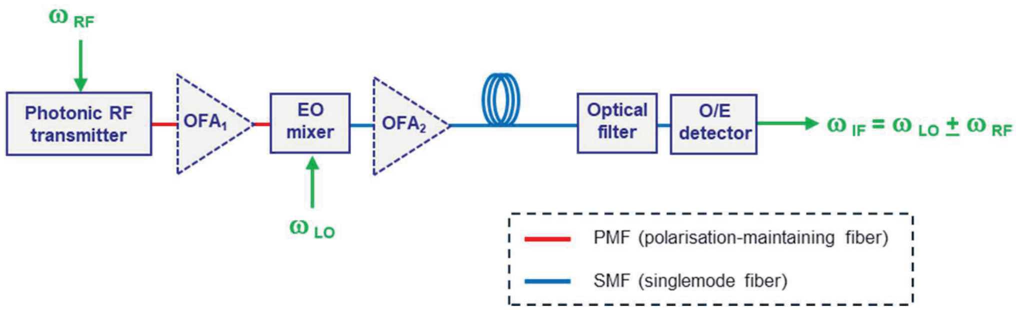
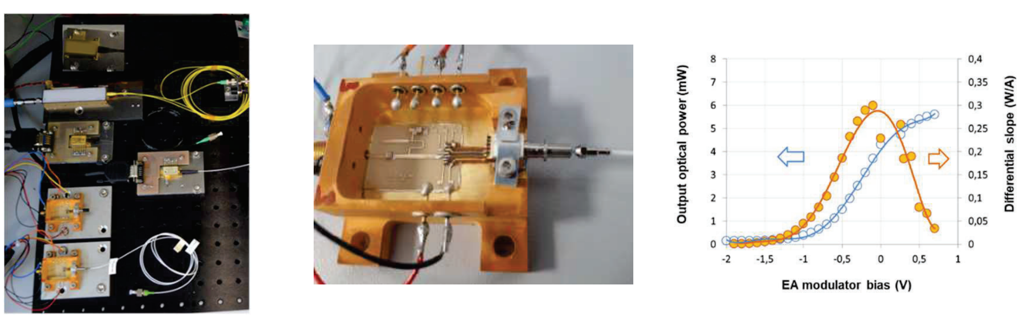


Figure 8. Reference configuration for photonic RF frequency conversion

A breadboard demonstrator of such a photonic RF frequency-converter was assembled at Thales Alenia Space in order to assess the RF end-to-end performance. Different types of potential photonic RF transmitters were considered and implemented i.e. a direct modulation laser (DML), an EML, a discrete Lithium Niobate MZM EO modulator (LN MZM) and an integrated Gallium Arsenide MZM EO modulator (GaAs MZM). The use of EML designed for digital applications was considered as it could provide an attractive trade-off covering RF performance, implementation complexity and SWaP.

Fig. 9 illustrates the work made in the implementation and optimization of the various photonic sources and in particular of EML components (Sumitomo Electronic device) for analog RF applications. Fig.-c above shows how the operating points (laser current, EA modulator bias voltage) were chosen and tuned to achieve a proper equivalent differential slope.



(a) (b) (c)

Figure 9. RF photonic transmitters for multi-RF photonic frequency conversion

(a) The different RF photonic transmitter options evaluated (EO MZM, DML and EML)
(b) EML in its test case with polarization maintaining fiber
(c) Emitted optical power and equivalent differential efficiency of an EML

The RF performance of such a photonic RF frequency up-converter was measured for input RF signals in C-band (around 6 GHz) as outgoing from a digital processor output port and an output frequency in Ka-band (around 20 GHz) corresponding to Ka-band payload transmit sections.
Measurements of the RF gain and noise figure were carried for the different types of photonic RF transmitter options and the results are reported in Fig. 10. Rather than considering than the absolute values of the RF gain and noise figure, it is worth comparing the relative performance achieved with each of the transmitter option, in particular because the use for instance of a band-pass optical receiver with higher RF gain (or trans-impedance) and lower thermal noise would significantly improve the functional RF performance in all configurations.

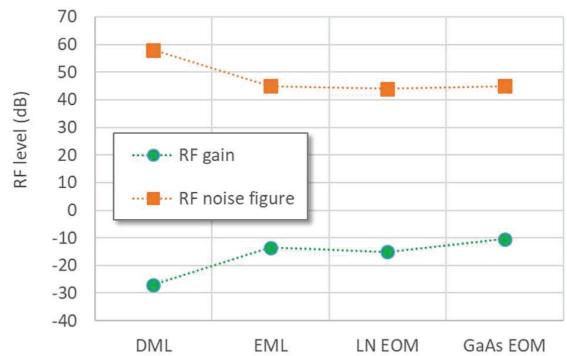


Figure 10. RF gain and noise figure of photonic frequency up-converter using various photonic RF transmitter types

The RF functional performance obtained with the two MZ type modulators and the EML were considered good enough. Only DML-based configuration was found to exhibit insufficient RF performance. The photonic RF frequency-converter configuration based on integrated GaAs MZM and EML device, in addition to offering good functional RF performance, hold higher potentials for integration than the other two technologies.
Thus the use of EML designed for digital applications and having RF bandwidth beyond the C-band, was found capable to provide a fair overall trade-off when encompassing RF performance and SWaP.

6. FREE-SPACE OPTICAL COMMUNICATIONS

FSO communications are becoming an essential part of current and future space solutions. High-capacity optical feeder links call for complex modulation formats at large data rate making EML not suitable for this application. On the contrary, EML is an interesting candidate for optical inter-satellite links in large LEO satellite constellations where SWaP and cost really matter. Hereafter are presented the performance obtained using an EML for digital and RF analog modulation.

The laboratory test-bed for FSO transmission is shown in Fig. 11. The transmitter unit is composed by an EML or alternatively a Laser + MZM (as a reference design), a WDM multiplexer and a high-power optical amplifier (HPOA) with > 1 W output power. The optical losses of the propagation channel are emulated using 2 variable optical attenuators (VOA) in series. The receiver unit includes a low noise optical amplifier (LNOA), a WDM which acts both as a demultiplexer and an optical filter and a PIN photodiode. Tap couplers are inserted in the link to monitor the optical power. The measurements are done using a BERT/scope for digital transmission, and a set of RF synthesizer and spectrum analyzer for RF analog transmission.
For digital applications, it is essential for the transmitter to achieve high dynamic extinction ratio. An EML device was found to achieve a relatively high extinction ratio (up to 12 dB at 25 Gbps), very similar as that obtained with a MZM-based transmitter.

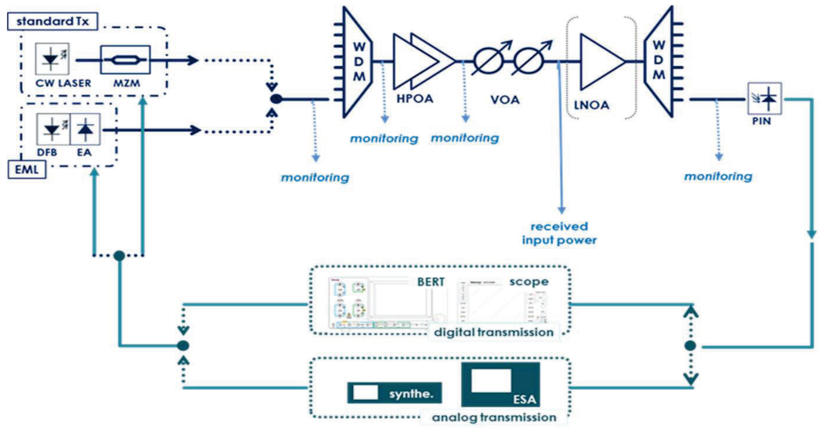
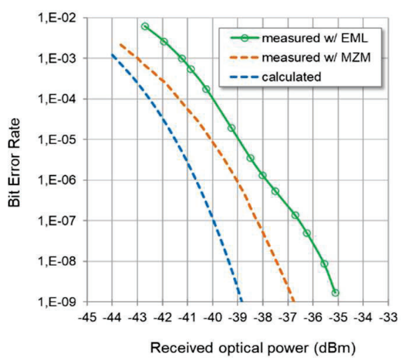


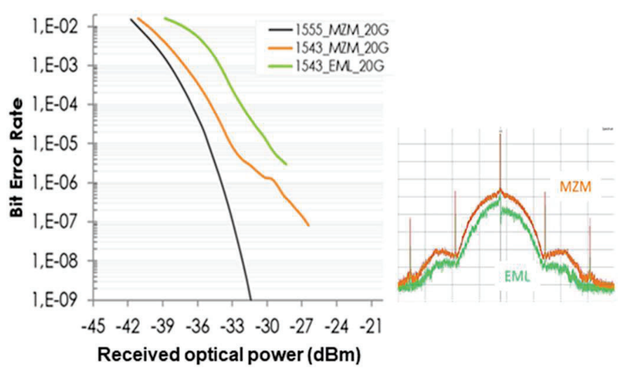
Figure 11. Test set-up for FSO transmission experiments

A 10G EML was tested for digital transmission at 10 Gbps in a full FSO link configuration with optical amplifiers. The BER is plotted as a function of the received optical power in Fig. 12 (a). For a BER of 10^{-4}, the received optical power penalty in detection sensitivity is not larger than 1.3 dB with respect to the value obtained with a conventional MZM-based transmitter architecture.

Similar transmission experiments were carried out at 20 Gbps using the Almae technologies EML, and the results are shown in Fig. 12 (b). The dynamic extinction ratio was in the same order (≈ 13 dB) for the EML and the reference transmitter. For the same wavelength (1543 nm), the power penalty (at 10^{-4} BER) between the EML and the reference is about 2.4 dB. This penalty has various origins. In particular, for optimal EML dynamic extinction ratio, eye diagram was not symmetric. Also EML frequency response (S_{21}) was not smooth after 8 GHz. We believe this can probably be overcome by improving the EML RF access.



(a) 10Gbps OOK



(b) 20Gbps OOK

Figure 12. Results of digital transmission experiments using EML and comparison with reference MZM-based transmitter

First assessment of RF analog transmission using the Almae Technologies EML was achieved at 20 GHz which corresponds to the transmit frequency in Ka-band. In RF analog applications, the carrier-to-noise ratio (C/N) is a key performance indicator. The carrier-to-noise ratio of the RF signal retrieved at the output of the optical receiver unit was measured as a function of the received optical power, and it was for different EML operating conditions. As shown in Fig. 13, very similar C/N curves were obtained with the EML-based and the MZM-based transmitters. These first evaluation results indicate that, again, attractive performance could be achieved.

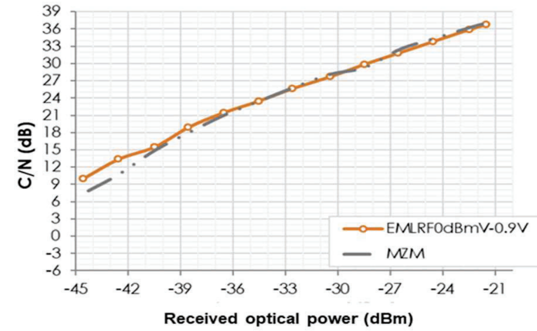


Figure 13. Analog C/N measurements for FSO transmission of RF signals at 20 GHz ; comparison between EML and MZM

7. CONCLUSIONS

Commercial 10/25G 1550 nm EML have been thoroughly evaluated and have shown promise for a number of analog and digital space applications. EML devices can be used effectively including at high frequency, instead of the conventional (laser + MZM) approach with almost no or small degradation. It was shown possible to design optical transmitters so as to reduce SWaP and cost while meeting the key performance. Through separated control of emission and modulation, EML-based solutions can provide a fair balance between integration and performance. Optical distribution of 13 GHz-LO was achieved with limited phase noise floor penalty compared to the MZM-based assembly. Photonic RF frequency-conversion was proven to perform better with EML than with direct modulation laser.
For FSO inter-satellite links in constellations where SWAP and cost really matter, EML-based transmitters are an interesting option. EML devices exhibited limited penalty in detection sensitivity in digital transmissions at 10 and 20 Gbps. For RF analog transmission, equivalent RF carrier-to-noise ratio performance were achieved at 20 GHz as well.
Through such experiments, Thales Alenia Space expands its experience with photonic technologies and sub-systems, and is better positioned to implement the most suitable solution for a particular application not only in terms of performance, but also in terms of implementation complexity, SWaP and cost.

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