EML Transmitter as Coherent Monitor for Distributed Spectrum Snooping

Bernhard Schrenk[1], Fotini Karinou[2]

[1]*Center for Digital Safety&Security, AIT Austrian Institute of Technology, Vienna, Austria*
[2]*Microsoft Research Ltd., Cambridge, United Kingdom*
**email: bernhard.schrenk@ait.ac.at*

Abstract. Awareness about the use of network assets and spectral resources in particular requires continuous and seamless monitoring throughout the network. Dense network architectures with high dynamicity in its highly populated links call for a distributed rather than a centralized approach so that the respective monitoring functionality should be integrated in all network terminals. In order not to introduce additional cost, we propose to re-use a transmitter that is widely adopted in direct-modulation / direct-detection systems as a spectral monitor. We experimentally demonstrate that an externally modulated laser is offering the functionality of a continuously tunable coherent receiver in order to down-convert optical signals to the RF domain for subsequent narrowband slicing and power integration. Modulation spectra for on-off keyed signals at different data rates and pulsed signals can be correctly acquired over a spectral range of 320 GHz, in virtue of the high resolution that the proposed coherent spectrum analyser is offering. The errors in wavelength and magnitude are less than 36 pm and 4.6 dB, respectively.

1 Introduction

Network control and optimization builds on the awareness about the use of actual physical layer assets in order to compute operational decisions. Spectral monitoring constitutes one of the pillars upon which this process is based [1]. As the networks grow denser, their loss budgets increase and the spectral link occupancy becomes more flexible, centralized monitoring is approaching its limits in providing a continuous and complete picture on the actual use of spectral resources at any point of the network. A possible path to address complex networks is a hybrid approach in which a centralized high-performance monitor is supported by a large number of distributed spectral analysers (Fig. 1). However, greatly simplified optics are required to economically justify such an approach. Classical spectral analysis relies on narrow tunable filters or specialised fibre setups, which are typically found in dedicated monitoring equipment [2] rather than in the transceivers sub-systems used for data transmission. This stands against the network-wide deployment of spectral "snooping" capabilities. Coherent detection with a tunable local oscillator (LO) offers an attractive alternative [3,4]; however, the complexity associated to coherent front-ends is practically limiting the application range to metro- and core networks.

In this work we propose the integration of spectral monitoring functionality in a state-of-the-art transmitter. We experimentally demonstrate that an externally modulated laser (EML) that is exploited as a tunable coherent receiver can embed a functional monitoring overlay in order to resolve the spectra of optical signals at high resolution. We show the acquisition of different modulation spectra over a spectral range of 320 GHz and analyse the estimation accuracy in terms of wavelength and magnitude error.

2. Methodology: EML-based spectral monitor

Figure 1 presents the use of a direct-modulation, direct-detection transmitter as spectral monitor. In a nutshell, an EML offers its capability as a continuously tuned coherent receiver in order to down-convert an optical slice to the electrical domain for subsequent integration of the RF power within an electrically defined resolution bandwidth.

In particular, the EML is exploited as coherent receiver through the use of its distributed feedback (DFB) section as LO [5]. Together with the optical input signal, this LO impinges on the electro-absorption modulator (EAM) that constitutes the photodetector. By tuning the DFB emission frequency ν^* through either current I [6] or temperature T [7] control, a spectral slice in the order of a few nanometres can be down-converted to the electrical domain for further processing. This analogue stage includes an RF passband filter that further narrows down the resolution bandwidth. At the same time, the centre of this filter is set close to zero to avoid ambiguity arising from the beating of the mirror frequencies. An RF power detector then yields an output that is proportional to the optical power P incident to the EML as function of the EML's actual emission frequency ν^* and the deviation $\Delta\nu^*$ that results from the detuned bias point.

In this way a simple optical transmitter, which is widely deployed in many telecom fields, is re-used for the purpose of distributed spectral snooping deep inside the network. There are only minor modifications required in terms of hardware, which are mostly related to low-frequency RF electronics. In order to retrieve reliable information about the acquired optical spectrum, it is paramount to calibrate the EML emission frequency $\nu^*(T,I)$ with respect to its absolute wavelength and the frequency deviation that results from an intended modification of the EML's bias points.

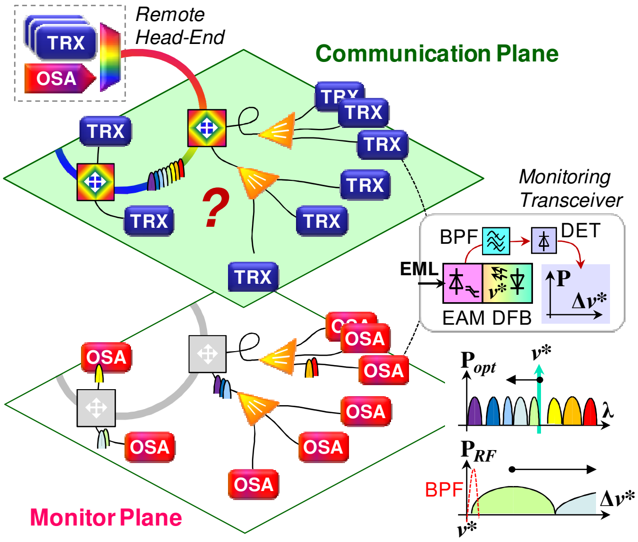

Fig. 1 Spectral monitoring integrated in EML transmitters.

3 Experimental setup and characterisation

The experimental setup to evaluate the EML-based spectral monitor is presented in Fig. 2(a). A comb of 8 channels from 1541.87 to 1552.52 nm is fed to the EML through a 27.5 km long feeder fibre. The 5 channels at ν_3 to ν_7 in the vicinity of the EML (ν^*, 1546.88 +/- 1.13 nm have been modulated with different modulation settings, including 2.5 (ν_4, ν_6, ν_7) and 5 Gb/s (ν_5) on-off keyed (OOK) data and a 1-GHz clock with 100-ps pulses (ν_3). The required drive for the Mach-Zehnder modulators (MZM) is supplied by an arbitrary waveform generator (AWG) and a pulse generator (PG), respectively. The electrical signal spectra are included in Fig. 2(a) together with the optical input spectrum to the EML.

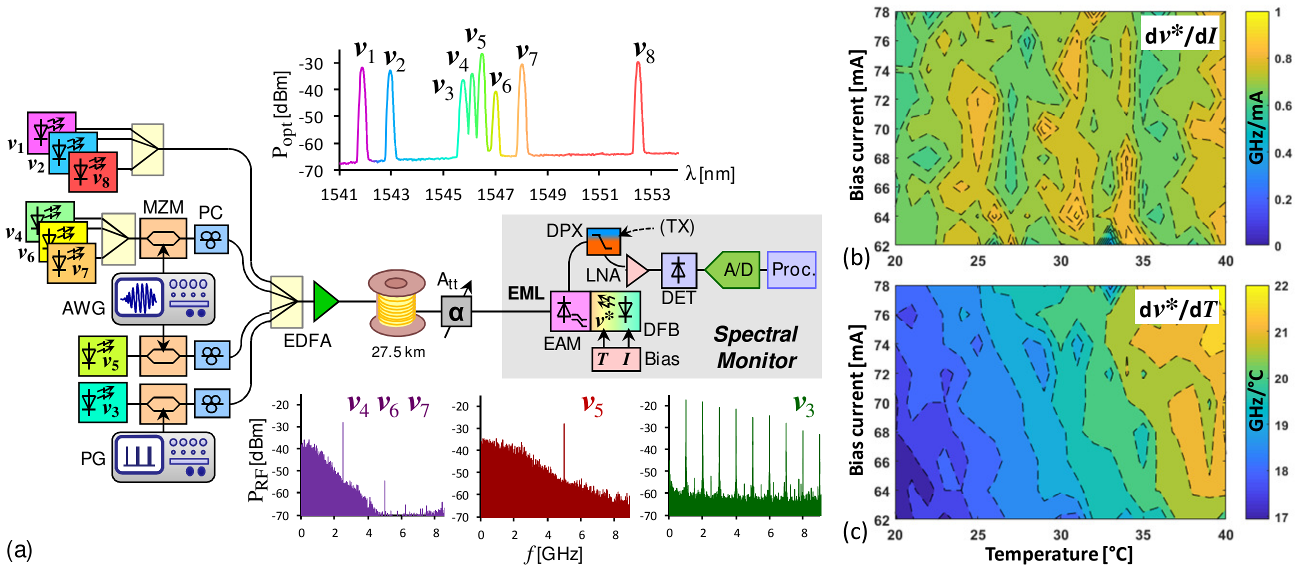

Fig. 2 (a) Experimental setup to evaluate the spectral monitor. The insets show the received optical spectrum and the electrical signal spectra at the particular channels. EML tuning efficiency for (b) current tuning and (c) temperature tuning.

The spectral monitor builds on the EML as coherent receiver, which is tuned through temperature and DFB current control at a fixed EAM bias of -0.7V. A duplexer (DPX) substitutes the passband filter function as RF branching device. In this way a simultaneous transmit path can be implemented [8] provided that its frequency range is not restricted through the monitoring function. In the present experiment a slice from 0 to 27 MHz is dropped by the DPX towards the monitor branch. Low-noise amplification (LNA) conditions the filtered signal and its integrated power is obtained through an RF detector (DET). After digitization of the detected power through a low-frequency analogue-to-digital (A/D) converter the signal deriving from the applied *T*/*I* sweep is analyzed.

For the sake of simplicity a single-polarization receiver was used and the launched polarization state was manually optimized (PC) for the signals. A diversity EML arrangement is required for polarization-independent operation [9,10].
Characterization data for the spectral tuning of the EML-based monitor is presented in Fig. 2(b,c). Values for the tuning efficiency in emission frequency are shown for a variation in DFB bias current and temperature, respectively, as function of the operation point (*T*/*I*). Measurement data has been obtained through heterodyning the EML output with a frequency-stable reference laser, which is also used to calibrate the EML emission frequency ν^*.
Current-induced tuning is widely independent of the EML's operation point and allows for fine tuning at ~0.75 GHz/mA. Coarse alignment over more than 300 GHz is conducted through temperature tuning. However, the efficiency varies from 18 to 21 GHz/°C. It depends on the actual point of operation and, particularly, on the actual temperature setting. This needs to be taken into consideration to obtain the actual frequency detuning for ν^* when performing a spectral sweep.

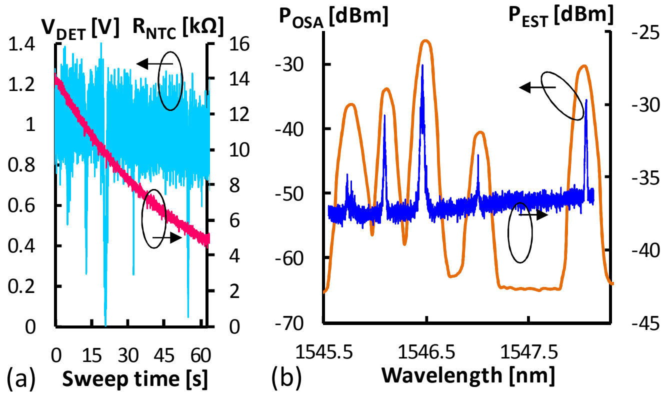

Fig. 3 (a) Raw monitor data and (b) estimated signal spectra.

4 Results: Spectral monitoring

Figure 3(a) shows a sub-set of the raw monitor data for a single sweep, including the actual thermistor resistance R_{NTC} of the EML and the detected RF signal V_{DET} after coherent reception and electrical slicing. By sweeping the EML emission frequency ν^* over its entire thermal range, the optical spectrum covering ν_3 to ν_7 is detected. Taking the wavelength calibration, tuning efficiencies and several receiver parameters such as EAM responsivity, RF gain and RF detection efficiency into consideration, an estimation on the signal spectrum can be made after noise filtering. The resulting estimated spectrum P_{EST} that is acquired through the EML-based monitor after a sweep over 320 GHz is shown in Fig. 3(b). For comparison, Fig. 3(b) also includes the spectrum P_{OSA} as obtained through an optical spectrum analyser (OSA) with a resolution bandwidth of 0.1 nm. The acquired spectrum and the estimated optical power $P_{EST}(\lambda)$ approximates that of the optical input signal $P_{OSA}(\lambda)$ with good agreement. Table I summarizes the difference between measurement with the OSA and the EML. The absolute error ε in center wavelength varies from -36 to +5 pm. The error π in magnitude reaches from -4.6 to +4.5 dB. It shall be stressed that the sensitivity of the monitor is to be further improved by substituting the LNA-based RF front-end by a transimpedance amplifier while also ensuring a higher dynamic range for the RF power detector.

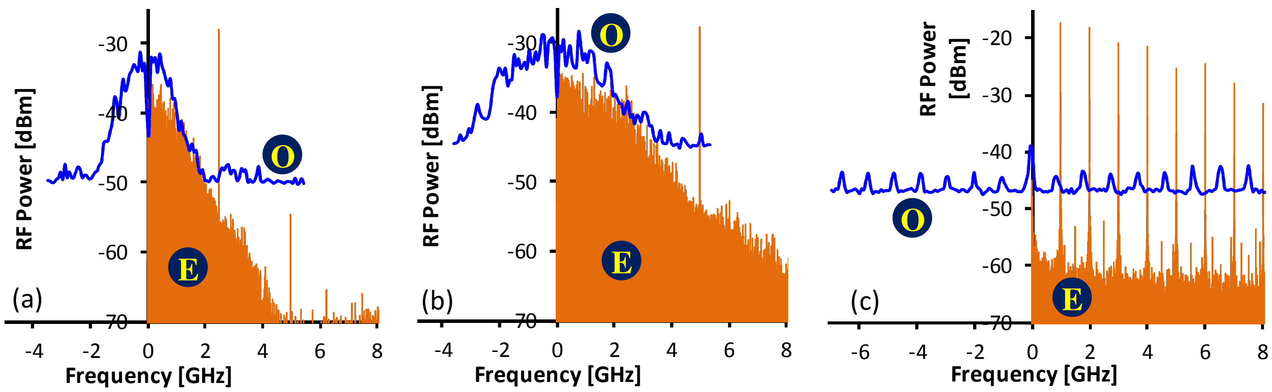

Fig. 4 (a) Acquired signal spectra for (a) 2.5 Gb/s OOK, (b) 5 Gb/s OOK and (c) 1-GHz pulsed clock.

At the same time, the coherent approach enables a much finer resolution, which allows to resolve the modulation spectrum rather than simply giving a power estimate for a particular channel. The capability to retrieve the modulation setting of the wavelength channels is demonstrated in Fig. 4. For this purpose the electrical transmission spectra (E) have been overlapped with the acquired signals (O), which are obtained through a step size of 100 µA for the DFB current sweep. Shown are the 2.5 Gb/s OOK signal at ν_3 (Fig. 4(a)), the 5 Gb/s OOK signal at ν_5 (Fig. 4(b)) and the 1 GHz pulsed clock at ν_4 (Fig. 4(c)). There is a good agreement with the modulation spectra in all cases, except for the precise overlap in clock harmonics for the last case. This is explained by the uncertainty in tuning efficiency, which leads to a mismatch in the spectral estimation. Moreover, the bandwidth of the DPX channel causes the clock harmonics to be washed out. The dips that can be noticed at the centre frequency of the OOK signals are explained by the injection-locking of the DFB laser, which suppresses spectral components within the locking range around the optical carrier of the OOK signal.

at	**OSA**		**EML monitor**	
	λ_{OSA}	P_{OSA}	λ_{EST} (ε)	P_{EST} (π)
ν_3	1545.75	-36.26	1545.73 (-18 pm)	-36.77 (-0.5 dB)
ν_4	1546.10	-33.86	1546.09 (-6 pm)	-34.69 (-0.8 dB)
ν_5	1546.50	-26.37	1546.46 (-36 pm)	-30.92 (-4.6 dB)
ν_6	1547.03	-40.52	1547.00 (-26 pm)	-36.03 (+4.5 dB)
ν_7	1548.05	-30.25	1548.06 (+5 pm)	-33.16 (-2.9 dB)

Table 1. Comparison between OSA and EML-based monitor.

5 Conclusion

We have demonstrated the re-use of direct-modulation / direct-detection transmitter technology for the purpose of high-resolution spectral monitoring. A device as simple as an EML is exploited as tunable coherent receiver in order to down-convert optical signals to the RF domain for subsequent passband filtering and detection. Spectral acquisition over 320 GHz has been shown to retrieve the signal spectra for various channels in good agreement with their actual modulation spectra. The accuracy in centre wavelength and magnitude has been evaluated. The use of an appropriate RF front-end promises simultaneous transmission with the same EML transmitter, thus integrating monitoring functionality seamlessly and deeply within the network.

6 Acknowledgements

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7 References

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