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Total number of authors:
16

Published in:
Journal of Lightwave Technology

Link to article, DOI:
[10.1109/JLT.2017.2651947](https://doi.org/10.1109/JLT.2017.2651947)

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Ozolins, O., Pang, X., Iglesias Olmedo, M., Kakkar, A., Udalcovs, A., Gaiarin, S., Navarro, J. R., Engenhardt, K. M., Asyngier, T., Schatz, R., Li, J., Nordwall, F., Westergren, U., Zibar, D., Popov, S., & Jacobsen, G. (2017). 100 GHz Externally Modulated Laser for Optical Interconnects Applications. *Journal of Lightwave Technology*, 35(6), 1174-1179. <https://doi.org/10.1109/JLT.2017.2651947>

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100 GHz Externally Modulated Laser for Optical Interconnects

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Abstract—We report on a 116 Gbps on-off keying (OOK), 4 pulse amplitude modulation (PAM) and 105 Gbps 8PAM optical transmitter using an InP-based integrated and packaged externally modulated laser for high speed optical interconnects with up to 30 dB static extinction ratio and over 100 GHz 3 dB bandwidth with 2 dB ripple. In addition, we study the trade-off between power penalty and equalizer length to foresee transmission distances with standard single mode fiber.

Index Terms—distributed feedback laser (DFB), direct detection, electroabsorption modulator, optical interconnects.

I. INTRODUCTION

The third generation 400 Gbps client-side links are demanding a solution as the cloud services together with the huge size datasets are driving demand for bandwidth in datacenters [1],[2]. Potential solutions are under discussion within the IEEE P802.3bs 400 Gigabit Ethernet (GbE) Task Force [3]. One attractive solution is based on eight optical lanes (i.e., 8×50 Gbps/ λ [4]) thanks to compatibility with existing building blocks for 100 GbE (drivers, lasers, and photodetectors with transimpedance amplifiers). However, large lane count increases complexity and power consumption resulting in higher costs [1]. More scalable and cost efficient approach is to reduce number of lanes and increase the bandwidth for a single lane. Four optical lanes at 100 Gbps net rate (i.e., 4×100 Gbps/ λ [5]) are a promising solution in order to reduce complexity, power consumption and costs.

Manuscript received; revised; accepted
Date of publication; date of current version
This work is supported by EU projects ICONe gr. #608099 and GRIFFON gr. # 324391, Swedish ICT-TNG program and Vetenskapsrådet project PHASE (grant no. 2016-04510). The equipment was funded by Knut and Alice Wallenberg foundation. The Tektronix is acknowledged for equipment loan.

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However, this task becomes even more challenging since it requires silicon and InP opto-electronic components with more than 70 GHz bandwidth.

Advanced modulations formats are extensively studied for short reach applications: (1) pulse amplitude modulation (PAM) [6]-[16], (2) carrierless amplitude phase (CAP) modulation [17], or (3) discrete multi-tone (DMT) [13],[18]. Such formats allow for more efficient bandwidth utilization at the cost of complex digital signal processing (DSP), which also may result in a higher costs and power consumption. These demonstrations usually require long digital filters resulting in complicated implementations. Hence, consensus seems to evolve towards 4PAM [6]-[16] and on-off keying (OOK) [14],[19]-[23] as it saves complexity on the transmitter side. Limiting amplifiers and electrical multiplexers technologies up to 120 Gbps have already matured into products. However, cost-efficient optical modulators at this bandwidth are not commercially available yet. PAM may reduce the bandwidth requirements, but it also reduces the receiver sensitivity and significantly complicates the electrical side of the transmitter (i.e., digital to analogue converters (DACs), linear drivers etc.). Therefore, higher bandwidth optoelectronic components with simpler modulation formats seem to be the most practical.

In this paper, we report on a cost-efficient integrated externally modulated laser (EML) with high bandwidth for 116 Gbps OOK (the first time achieved on a single EML [20] with low complexity DSP) and linear enough to accommodate 116 Gbps 4PAM and 105 Gbps 8PAM, while requiring a driving voltage of 2 V_{pp}, paving the way for high speed multilevel modulation formats.

This paper is organized as follows. Section II summarizes the related works and provides description of the externally modulated laser. In Section III, the experiment setup is detailed. The experimental results are shown and complemented with system simulations in Section IV. The conclusions are drawn in Section V.

II. EXTERNALLY MODULATED LASER

A. Previous Experimental Demonstrations

The optical transmitter is based on a monolithically integrated distributed feedback laser with traveling-wave electroabsorption modulator (DFB-TWEAM) designed by

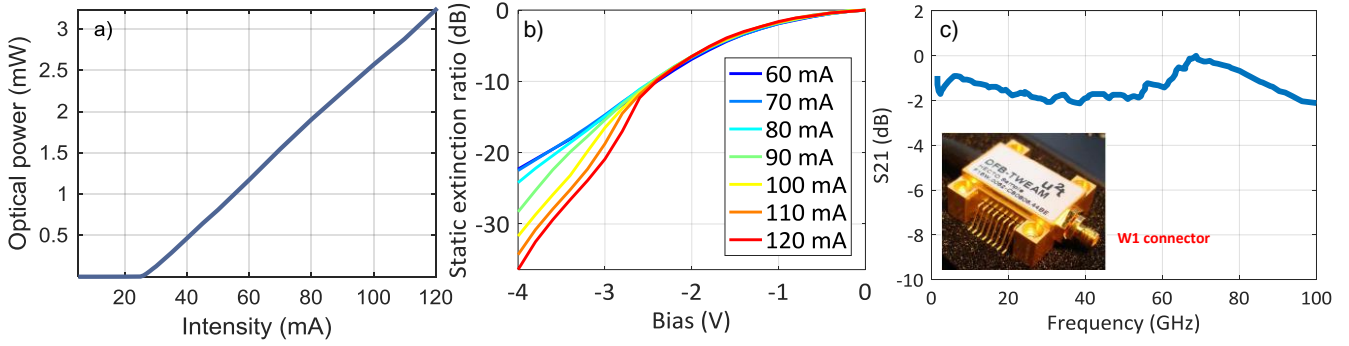


Fig. 1. a) $P(I)$ characteristics for unbiased modulator b) static extinction ratio characteristics c) $S21$ characteristics as measured in [22].

KTH, fabricated by KTH and Syntune and packaged by u²t Photonics [22],[23]. In [23], the performance of already packaged DFB-TWEAM transmitter module for 100 Gbps data rate is evaluated experimentally using 100 meters long standard single mode fiber (SSMF) and 10 km optical link with dispersion management. In [21] successful field trial is demonstrated with transmission of 112 Gbps OOK signals using a purely electrical time division multiplexing-based system without DSP. A bit error rate (BER) performance below the forward error correction (FEC) threshold of $2 \cdot 10^{-3}$ is achieved after transmission over 42 km field installed SSMF with dispersion management between Kista and Råsunda in Sweden. It is the first demonstration of a complete 112 Gbps ETDM system based on monolithically integrated transmitter [23] and receiver modules.

B. Device Structure and Characterization

The TWEAM is based on the 12 strain-compensated InGaAsP quantum wells/barriers (QWs) of around 9 nm thickness each. The total active length of modulator is 180 μm . The gain section of the DFB is based on 7 QWs 7 nm thick grown by metal vapour phase epitaxy coupled with butt-joint technique. The laser is 440 μm long with a grating designed to have most of the output power towards the modulator. Components are formed in standard ridge waveguide structures [22]. Figure 1 shows the power versus current for unbiased modulator, power versus bias voltage and

the frequency response taken at 22° C [24]. As we can see from Fig. 1a, the threshold current is ~ 25 mA, and the slope efficiency is .04 W/A, which allows us to reach about 2 mW with only 80 mA driving current. Fig. 1b shows the static extinction ratio versus bias voltage. We can observe that the device has a static extinction ratio in the range of 20 to 35 dB. The dynamic extinction ratio during modulation is related to modulator bias voltage and swing of driving voltage. The $S21$ curve of the device [22] (W1 connector) depicted in Fig. 1c clearly shows beyond 100 GHz 3 dB bandwidth, the highest reported bandwidth to the best of our knowledge, with less than 2 dB ripple in the pass band of the EML [22] which indicates high phase linearity. These figures of merits [22] are order of magnitude better than state-of-art EMLs for optical interconnects.

III. EXPERIMENTAL SETUP

Figure 2 shows the transmitter setup for 116 Gbps OOK, 4PAM and 105 Gbps 8PAM with receiver setup including DSP (see Fig. 2a) and output optical spectrum of modulated signals (see Fig. 2b). In the OOK setup, two pseudo-random bit sequences with a word length of $2^{15}-1$ (PRBS15) at 58 Gbps are first decorrelated and then multiplexed into a single 116 Gbps sequence. A 110 GHz traveling-wave limiting amplifier (TWA110 [25]) is used to drive the EML. In the 4PAM setup, two PRBS15 are first decorrelated and then

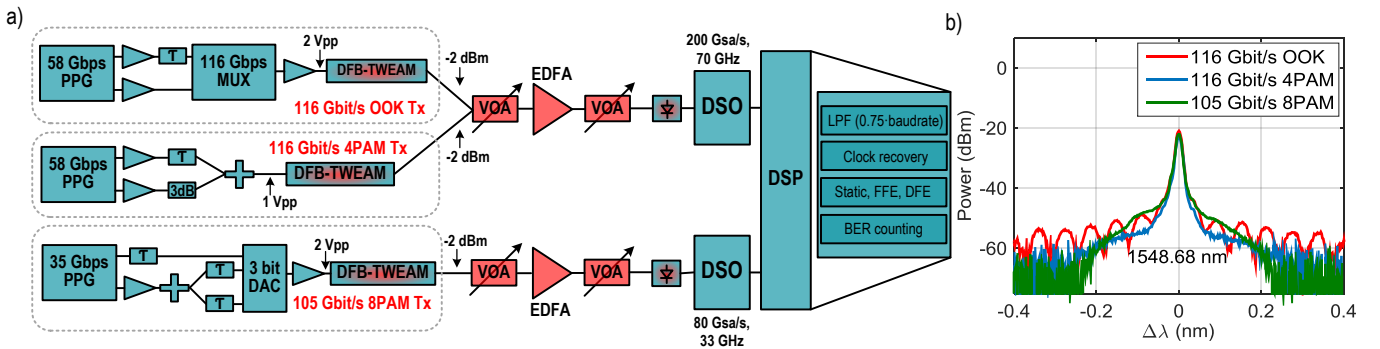


Fig. 2. a) Experimental setup. (PPG: pulse-pattern generator, Mux: Multiplexer, DAC: digital to analog converter T: Delay line, EDFA: erbium doped fiber amplifier, PD: Photodiode, DSO: digital storage oscilloscope, DSP: digital signal processing, LPF: low pass filter, FFE: Feed forward equalizer, DFE: decision-feedback equalizer). b) Optical spectrum of the modulated signals (@ 0.01 nm resolution bandwidth).

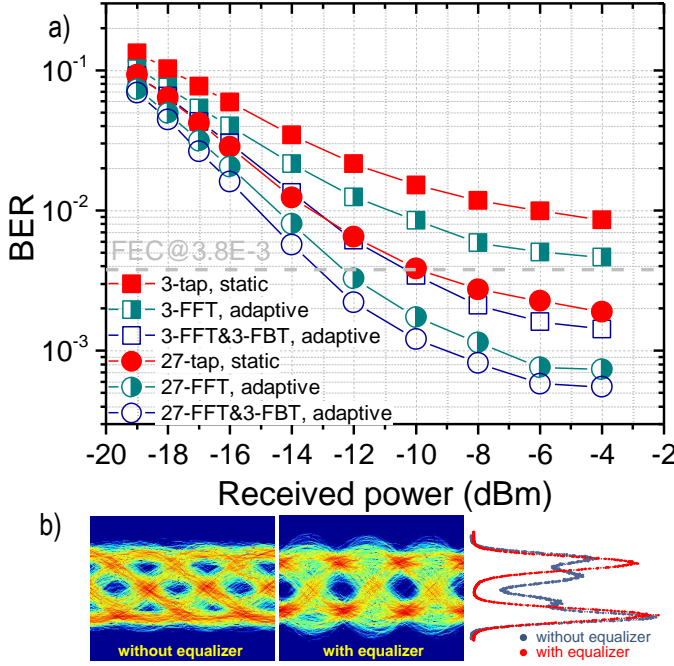


Fig. 3. a) BER curves for 116 Gbps OOK. b) Received eye diagram without and with equalizer and histograms for 116 Gbps OOK at -2 dBm input power.

passively combined into a 4PAM signal, which is then used to directly drive the EML. In the 8PAM setup, three PRBS15 sequences at 35 Gbps are first decorrelated and then combined in a 3 bit DAC with 19 GHz analogue bandwidth. A 65 GHz linear amplifier is used to drive the EML. During measurements the bias voltage was kept at minus 2 volts and driving voltage was 2 Vpp for OOK, 8PAM and 1 Vpp for 4PAM. The average output power was kept at minus 2 dBm in all cases. The receiver is composed of an Erbium doped fiber

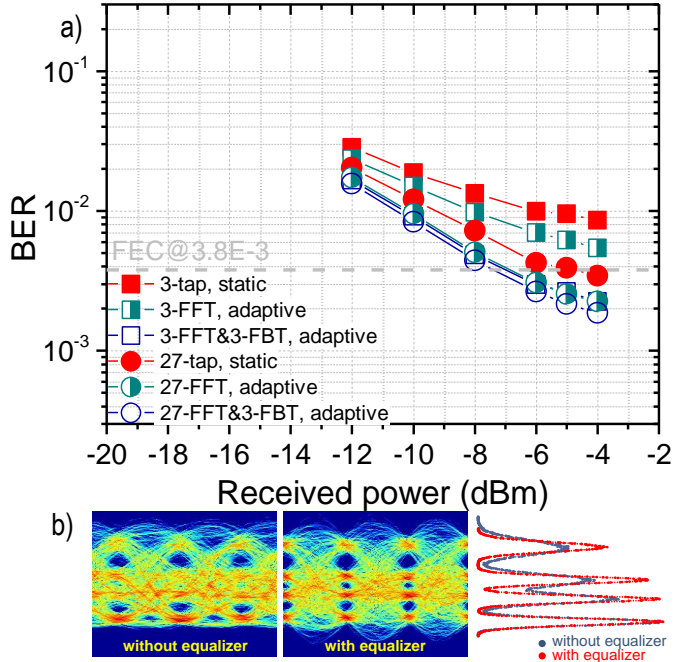


Fig. 4. a) BER curves for 116 Gbps 4PAM. b) Received eye diagram without and with equalizer and histograms for 116 Gbps 4PAM at -2 dBm input power.

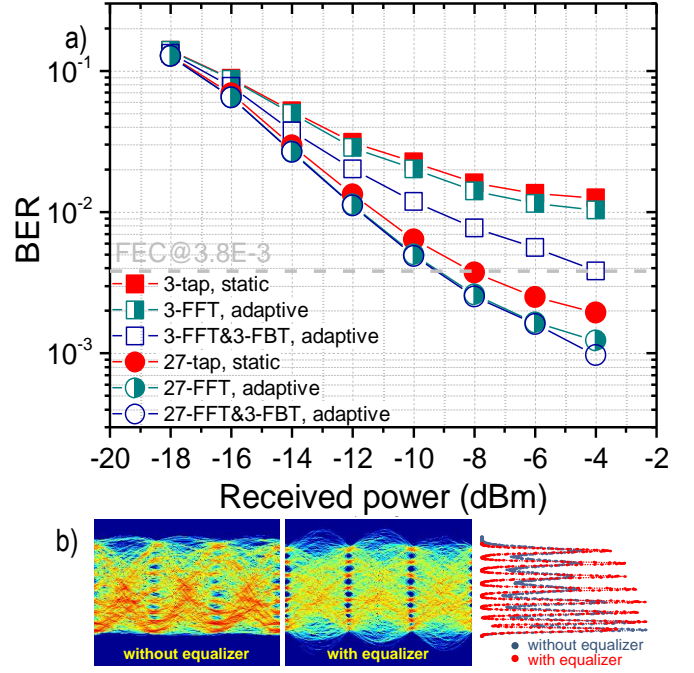


Fig. 5. a) BER curves for 105 Gbps 8PAM. b) Received eye diagram without and with equalizer and histograms for 105 Gbps 8PAM at -2 dBm input power.

amplifier (EDFA), variable optical attenuator (VOA), a high bandwidth photodiode (PD) from u^2t with a responsivity of 0.5 A/W, and a 200 GSa/s, 70 GHz bandwidth Tektronix digital sampling oscilloscope (DSO) (DPO77002SX) for OOK as well as 4PAM setups, while 80 GSa/s, 33 GHz DSO - for 8PAM setup. An automatic gain-controlled EDFA with fixed output power is employed as a pre-amplifier due to the low PD responsivity and the lack of transimpedance amplifier. The sampled signal is then processed offline using DSP. The clock recovery and resampling is performed on the received waveform. The signal is then downsampled to 1 sample per symbol for static/adaptive feed forward equalizer (FFE) with different number of taps to overcome inter symbol interference (ISI) or symbol-spaced adaptive decision-feedback equalizer (DFE) with different configuration of feed-forward taps (FFT) and feedback taps (FBT) to overcome ISI in presence of noise. The initial weights of the equalizer were obtained using training data with the normalized least-mean-square (NLMS) algorithm before applying other data. A total number of 1.2 million bits are used for BER counting. The bandwidth limitation is due to limited effective 3 dB bandwidth on the transmitter side components used to generate electrical signals, while additional filtering occurs due to the limited DSO bandwidth, affecting the performance of OOK and 8PAM setups.

IV. RESULTS AND DISCUSSIONS

Obtained results provide the quantitative and qualitative performance evaluation of the optical transmitter for its capabilities to enable the third generation 400 Gbps client-side links for optical interconnects. Figure 3 shows BER curves for 116 Gbps OOK (see Fig. 3a) and the qualitative measure in

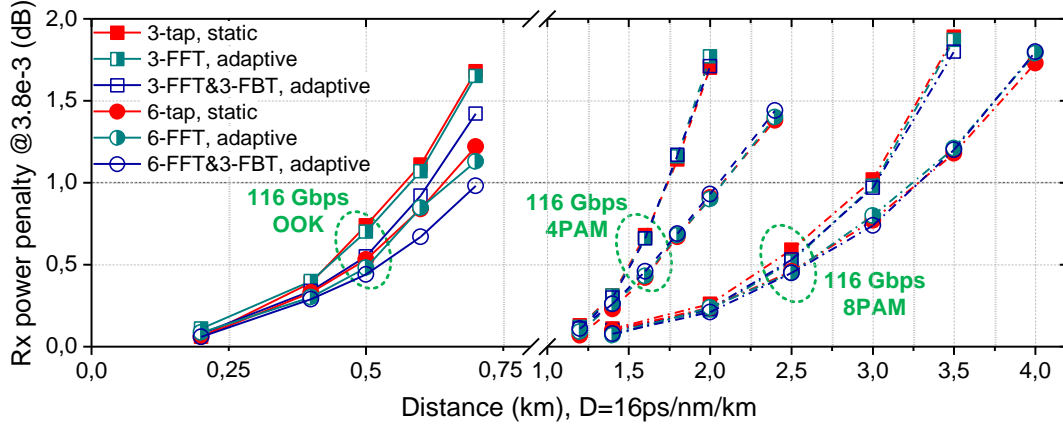


Fig. 6. Received power penalty as function of transmitted distance for 116 Gbps OOK, 4PAM and 8PAM for different equalizer configurations (see inset).

terms of eye diagram and the histogram distribution of the received signal (see Fig. 3b). BER curves are obtained using 3-tap and 27-tap static filter, 3-FFT and 27-FFT adaptive FFE, and 3-FFT&3-FBT and 27-FFT&3-FBT DFE. One can observe that the use of 3-FFT&3-FBT DFE allows achieving below 7% FEC limit performance, which was further improved with larger lengths of equalizers. Adding small feedback in equalizer allows significantly improving the performance. We also observed that 27-tap static filter allows achieving almost the same performance as 3-FFT&3-FBT DFE. Performance is further improved by 3 dB (reduction in power penalty) with 27-FFT&3-FBT DFE. Figure 3b shows the received eye diagrams and histograms with and without equalizer for 116 Gbps OOK signal. We can see that the signal is limited by both ISI and noise. The histogram without equalizer shows level degeneration owing to the ISI which we also observed in the electrical signal.

Figure 4 shows BER curves (see Fig. 4a), eye diagrams and histograms (see Fig. 4b) before and after equalizer for 116 Gbps 4PAM. BER curves are obtained using same equalizers as in OOK case. We can see large degradation on the 4PAM signal owing to both higher sensitivity requirements and poor electrical signal performance at the transmitter. After equalizer one can observe that passive combining ratio is suboptimal (see transmitter design in Fig. 2a), which explains the worse performance. We use the EML to compensate this effect by driving it at high reverse bias voltage (-2 volts). We are able to improve the performance, however, this causes compression on the upper levels and thus a trade-off was found. By adding 3-FFT&3-FBT DFE, a BER below FEC limit was achieved. We did not observe significant improvement by increasing the length of equalizer.

Figure 5 shows BER curves for 105 Gbps 8PAM (see Fig. 5a) and eye diagram and the histogram distribution of the received signal (see Fig. 5b). Similarly to previous cases BER curves are obtained using same configuration as before. Sensitivity for 8PAM is lower than 4PAM, but thanks to the performance of the 3 bit DAC, the implementation penalty is lower. However, still some compression is observed. One can

observe that the performance of 3-FFT&3-FBT DFE is below the 7% FEC limit. Still performance can be significantly improved (reduction in power penalty is 4dB with 27-tap static filter and 5 dB with 27-FFT&3-FBT DFE) with increased length of equalizer since the main bandwidth limitation is the 19 GHz bandwidth of the DAC. Therefore, by ensuring sufficient bandwidth in the electrical domain, the optical transmitter has the potential of transmitting >100 Gbaud signals with low DSP requirements.

Operational wavelength of the EML is around 1548 nm in these measurements. To complement the experiments we study chromatic dispersion tolerance for different modulation formats using Monte Carlo simulations. In simulation we assumed that all modulation formats are operated at 116 Gbps for a fair comparison. In simulations we focus on tolerance to chromatic dispersion (16ps/nm/km). Only bandwidth limitation is PD with responsivity of 0.5 A/W and 80 GHz bandwidth. Received power penalty as function of transmitted distance is shown in Fig.6. We obtain curves for 3-tap and 6-tap static filter, 3-FFT and 6-FFT adaptive FFE, and 3-FFT&3-FBT and 6-FFT&3-FBT DFE. For 1 dB power penalty, the 116 Gbps OOK format can be transmitted up to 700 meters using 3-FFT&3-FBT DFE. The distance for 116 Gbps 4PAM can be increased about three times compared to OOK for same penalty and equalizer parameters. In case of 116 Gbps 8PAM, the dispersion penalty will be below 1 dB at 3 km distance using only a 3-tap static filter.

We point out that the microwave design of the transmitter can be applied to a semiconductor material with larger bandgap in order to achieve modulation at another operation wavelength [23]. Then transmission distances over SSMF can be significantly improved.

V. CONCLUSIONS

We report on the performance of an EML with higher than 100 GHz bandwidth for optical interconnects. We experimentally validate its potential for fast optical interconnects by transmitting 116 Gbps OOK, 4PAM and 105 Gbps 8PAM signals. Furthermore, this is the first time [20] that 116 Gbps OOK is achieved on a single EML based

optical transmitter with low complexity DSP. We study the trade-off between power penalty and equalizer length using Monte Carlo simulations. According to simulation results, a transmission of 3 km standard single mode fiber with less than 1 dB dispersion penalty using only 3-tap static filter for 116 Gbps 8PAM seems to be possible. We conclude that, provided sufficient bandwidth and linearity on the electrical domain, this optical transmitter can be used for advanced modulation formats at higher than 100 Gbaud.

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Fredrik Nordwall, biography not available at the time of publication.

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Klaus M. Engenhardt, biography not available at the time of publication.

Tadeusz Asyngier, biography not available at the time of publication.

Darko Zibar, biography not available at the time of publication.

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