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Special Focus on Photonic Devices and Integration

A 70 Gbps NRZ optical link based on 850 nm band-limited VCSEL for data-center intra-connects

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Abstract Short-reach optical interconnects among servers in data centers have attracted extensive studies recently. High capacity and low cost are two key problems for optical link. In this paper, we demonstrate a band-limited 850 nm vertical cavity surface emitting laser (VCSEL) based optical transmission system. The optical link realizes 70 Gb/s (65 Gb/s net rate) non-return-to-zero (NRZ) signal transmission over 11 m and 20 m OM4 multimode fiber (MMF), with the help of equalization for time domain interference elimination. The utilized VCSEL has a bandwidth of only 18 GHz, meeting the principle of low cost. The data baud rate in this paper reaches the highest value for an 18-GHz-class 850 nm VCSEL based optical link, to our best knowledge.

Keywords 850 nm VCSEL, band-limited, 70 Gb/s NRZ, OM4 MMF, equalization

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1 Introduction

With the ever increasing data stream in end users' daily life, data centers will meet great challenges for being upgraded [1]. Short reach optical interconnects among servers in data centers have shown their enormous potential to satisfy the demands for both processing and storage resource sharing. Recently, short reach optical communication systems in data centers mainly consist of low-cost vertical cavity surface emitting lasers (VCSELs), multimode fiber (MMF), and photodiodes (PDs) for direct detection. It has been indicated that directly modulated VCSELs and MMF would guarantee servers, high performance computing (HPC) and some datacenter needs for quite a long time in the future [2]. Besides, the technology based on multimode VCSEL, mainly in 850 nm, is regarded as the cheapest and lowest power approach for short-reach interconnects in the foreseeable future [3].

Since the optical interconnects systems based on ON-OFF keying (OOK) are cost efficient and with low power consumption, OOK is the leading modulation type in the commercial links today [4]. Meanwhile, other complex modulation formats have also been utilized in this area to improve the transmission rate, such as, multilevel pulse amplitude modulation (PAM), discrete multi-tone (DMT) modulation, and carrier-less amplitude phase (CAP) modulation. Furthermore, equalization and forward error correction (FEC) are essential for most high-speed short-reach optical links. Szczerba et al. [5] proposed a 60 Gb/s PAM4 error free transmission via 2 m OM4 MMF employing 24 GHz 850 nm VCSEL, and 70 Gb/s

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PAM-4 modulated error free link using 25 GHz 850 nm VCSEL via 50 m OM4 MMF after FEC of Reed-Solomon (RS) codes and off-line equalization [3]. They showed a 94 Gb/s PAM-4 effective data rate employing pre-emphasis, and receiver equalization in 2016 [6]. Karinou et al. [7] employed FFE+MLSE-1024 equalization and realized 112 Gb/s PAM-4 transmissions via 100 m OM4 MMF. Finisar Corporation presented a result of 56–93 Gb/s DMT modulated link using 850 nm 25 GHz commercial VCSEL via 0–200 m OM3 MMF [8]. Puerta et al. [9] presented an effective bit rate of 100 Gb/s transmission utilizing multi-band CAP modulation through a 26 GHz (6 dB-bandwidth) multimode VCSEL and 10 m OM4 MMF. IBM T. J. Watson Research Center has shown the rate record for non-return-to-zero (NRZ) modulated 850 nm VCSEL, which is a 71 Gb/s error free optical link via 7 m OM3 MMF in 2015, utilizing 26 GHz VCSEL and without FEC [10]. The record of highest speed and distance for 850 nm VCSEL link is created by Huawei in 2016, giving a result of 150 Gb/s 13-level duobinary-PAM4 via 23 GHz VCSEL and 100 m MMF [11].

High order modulations, such as PAM-4, could increase the bit rate for transmission, but they bring in more power consumption and give rise to undesired latency. Therefore NRZ signal is more preferred for servers in reality [12]. IBM has predicted that the devices must have the bandwidth of 40 GHz or higher if employing directly modulated VCSEL for beyond 100 Gb/s NRZ [3]. Nevertheless, improving the bandwidth of VCSELs leads to extremely high cost. Most recent results focused on high capacity in the optical link only and employed advanced VCSELs with bandwidth of about 25 GHz class, which are against the original intention for low-cost optical interconnects in data centers [13]. In this paper, we use a commercial band-limited and cost-efficient VCSEL with the bandwidth of only 18 GHz directly modulated by 70 Gb/s NRZ signal, transmitting via 11 m and 20 m OM4 MMF, respectively. However, the 18 GHz band-limit VCSEL seriously damages the emission signal, as a result that the received signal after MMF and PD suffers severe inter-symbol interference (ISI). Therefore, advanced equalization methods for time domain interference elimination are needed. In this paper, we employ a combination of conventional linear feedback forward equalizer (FFE) and different-state (4, 8, and 16 states) maximum likelihood sequence estimation (MLSE) to eliminate the ISI. Finally, both 11 m and 20 m OM4 MMF links realize successful transmission with 65 Gb/s net rate, ensuring the bit error rate (BER) lower than 4.5×10^{-3} (7% hard-decision FEC threshold). Compared with the NRZ record result in [10] (7 m OM3 MMF transmission, 71 Gb/s using 26 GHz VCSEL), the result in this paper has significant advantages over distance (up to 20 m OM4 MMF) and bandwidth efficiency (65 Gb/s using 18 GHz VCSEL). Moreover, it is worth mentioning that several low-power and high-performance chips are proposed with the development of the digital signal processing (DSP) integrated circuit, such as the FlexPhy in MultiPhy (about 15 pJ/bit processing power consumption for over 100 Gbps transmission including ADC and DAC combined with MLSE DSP scheme), which indicates that the results in this paper would be realized as real-time transmissions in the foreseeable future.

2 Experimental configuration

Figure 1 illustrates the experimental configuration of the 70 Gb/s NRZ transmission through the band-limited VCSEL based optical link. The 850 nm VCSEL (New Focus 1784) is a multimode commercial laser and has a bandwidth of only 18 GHz. The 70 Gb/s electrical NRZ driving signal for transmitter, with a peak-to-peak value of 400 mV, is generated from an arbitrary waveform generator (AWG, MICRAM-VEGA-DAC3, 24 GHz 3 dB bandwidth and 72 GS/s max sampling rate). The DC bias current for VCSEL in directly modulation is selected as 1.4 mA. The emitted light is coupled into a standard OM4 MMF with a choice of 1 m or 10 m, and there exists a variable optical attenuator (VOA) to control the received optical power, connecting to another OM4 MMF. The PD is New Focus 1484-A-50, which has a bandwidth of 22 GHz. The optical signal is transformed into electrical signal via PD, detected by a high-speed real-time digital storage oscilloscope Agilent DSAX96204Q with 63 GHz bandwidth and 160 GS/s sampling rate. Before the oscilloscope, the signal is amplified by an electrical amplifier (EA) SHF S807 with a bandwidth around 50 GHz.

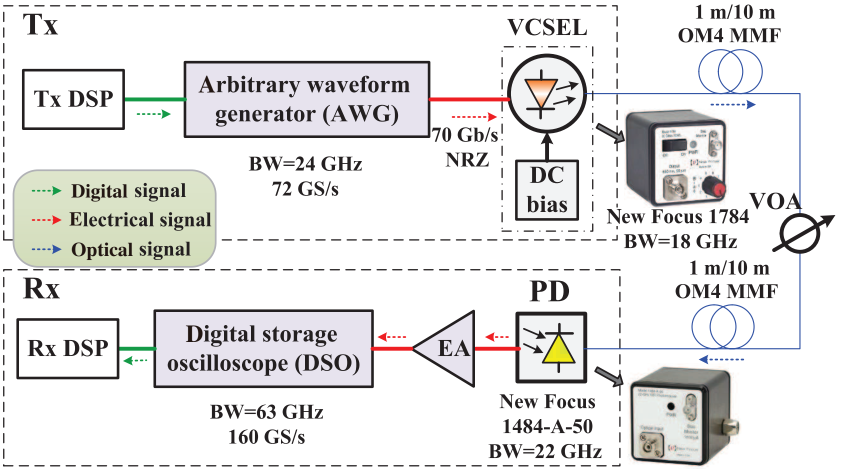


Figure 1 (Color online) Experimental setup.

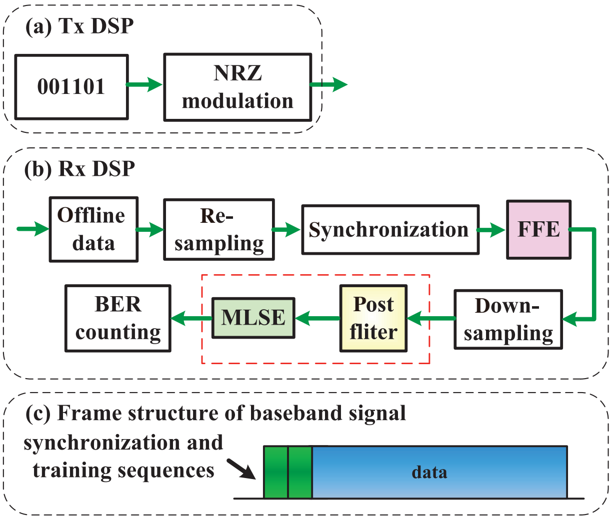


Figure 2 (Color online) Block diagram of DSP. (a) Tx; (b) Rx; (c) frame structure of the baseband signal.

The block diagram of DSP is shown in Figures 2(a) and (b). The structure of the transmitted baseband signal frame is shown in Figure 2(c). There are 655 data symbols used for synchronization and training sequences, and 2^{15} data symbols are transmitted after the preamble. At the transmitter, the 0/1 data stream is NRZ modulated to drive the AWG (sampling rate $F_\mathrm{s} = 70$ GS/s). At the receiver, this paper conducts the DSP to eliminate the ISI. The offline data is firstly re-sample to $2 \times F_\mathrm{s}$. Next, extracting timing information from the offline data and performing synchronization are essential. After that, a combination of FFE with the MLSE algorithm is used. Figure 3 illustrates the detailed DSP equalization configuration. The FFE equalizer is a $T_\mathrm{s}/2$ ($T_\mathrm{s}/2$ means the symbol time period, $T_\mathrm{s} = 1/F_\mathrm{s}$) spaced finite impulse response (FIR) filter with 41 taps, which is extracted from the training sequence. Then, down-sampling is carried out. An optimized FIR post filter is utilized before Viterbi algorithm (MLSE) to suppress the enhanced noise caused by FFE. In such a band-limited system, FFE would enhance the in-band high frequency noise. Figure 4 demonstrates the principle of filters, in which the post filter can be understood as a whitening filter. The MLSE, employing a memory length of 2, 3, and 4 (i.e., 4, 8, 16 states), which have corresponding post filters of $H(z) = 1 + \alpha z^{-1}$, $H(z) = 1 + \alpha z^{-1} + \beta z^{-2}$, and $H(z) = 1+\alpha z^{-1}+\beta z^{-2}+\gamma z^{-3}$, calculates the accumulated Euclidian distance between the received signal and the expected value to detect the most likely emitted bit sequence from the raw data. Meanwhile, MLSE is an effective elimination method for the ISI in time-domain, which has been considered as the best direct-detection DSP scheme in low-cost and low-power data center applications. Finally, the BER

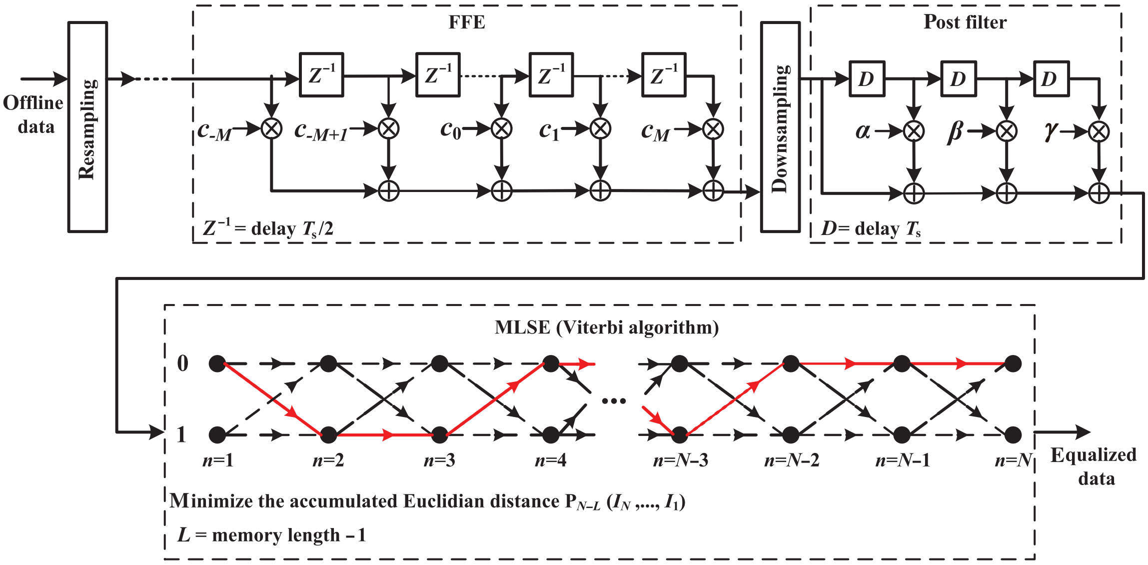


Figure 3 (Color online) DSP equalization configuration.

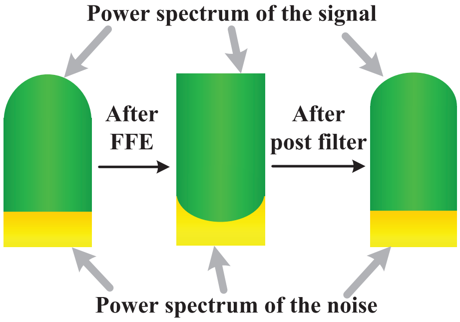


Figure 4 (Color online) Principle of filters.

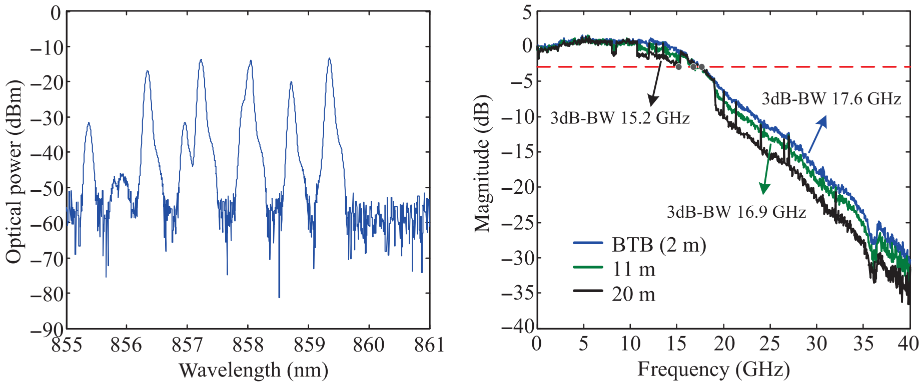
is calculated both at the output of the FFE and the output of the MLSE algorithm to explore the applicability of each approach under different transmission cases.

3 Experimental results

Figure 5(a) shows the optical spectrum of the multimode VCSEL. It has multiple peaks with the center frequency of around 858 nm. Figure 5(b) presents the frequency responses of different VCSEL-MMF-PD links. The 3-dB bandwidth of the link for back to back (BTB), 11 m OM4 MMF and 20 m OM4 MMF are 17.6, 16.9 and 15.2 GHz, respectively.

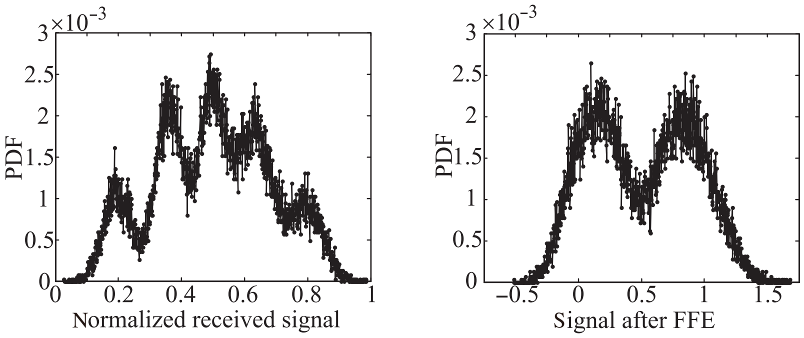
Figure 6 presents the distribution of the received signal when the condition is BTB and the received optical power is 0 dBm. Figure 6(a) shows the probability distribution function (PDF) of the normalized received signal without any equalization, and it is found that the received data are totally disordered, caused by ISI. Figure 6(b) gives the PDF of the signal after FFE, in which most data has been corrected to the right region while further DSP is still needed to improve the communication quality.

In order to verify the DSP algorithm and the principle of filters, Figure 7 gives the digital power spectrums of the received signal (BTB, received optical power = 0 dBm). Figures 7(a) and (b) are the digital power spectrums before and after FFE, respectively, in which the sampling rate is $2F_s$ (140 GHz). Comparing the two figures, it is found that the FFE significantly enhances the in-band high frequency signal (including noise) to suppress the ISI. Figures 7(c)–(e) give the digital power spectrums after the post filter with the corresponding order of 1, 2 and 3, respectively, in which the sampling rate is F_s (70 GHz). Compared with Figure 7(b), the later three spectrums have lower in-band high frequency



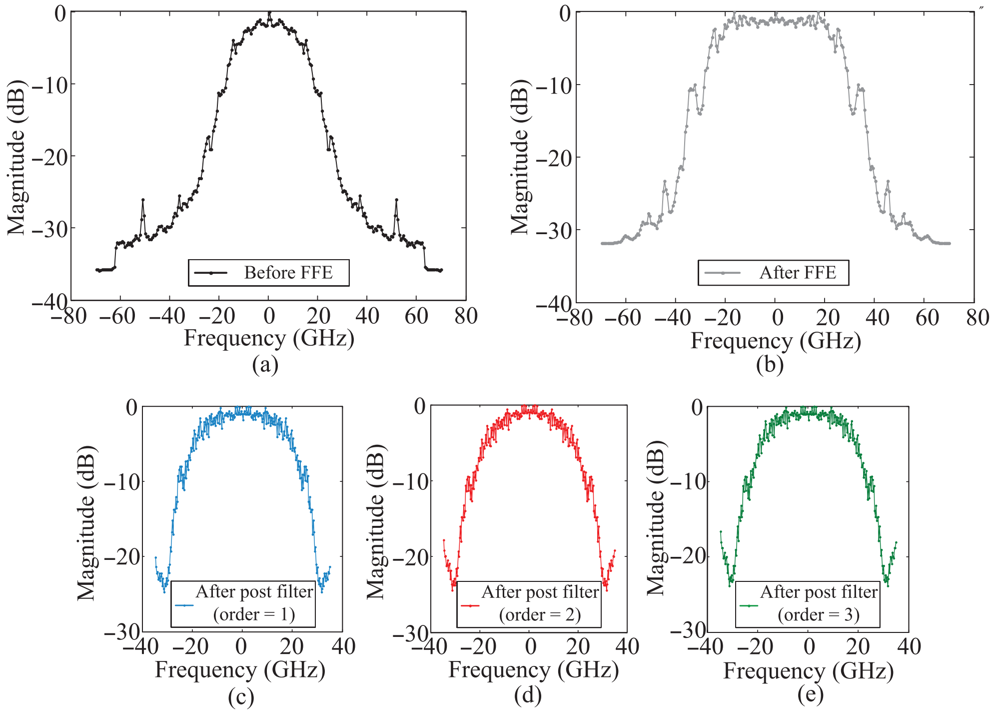
(a) (b)

Figure 5 (Color online) Characteristics of the transmission link. (a) Optical spectrum of the 18 GHz 850 nm VCSEL; (b) frequency responses of the VCSEL-MMF-PD link.



(a) (b)

Figure 6 The received signal distribution. (a) Before FFE; (b) after FFE.



(c) (d) (e)

Figure 7 (Color online) Digital power spectrums. (a) Before FFE; (b) after FFE; (c)–(e) after post filter (order = 1, 2, 3).

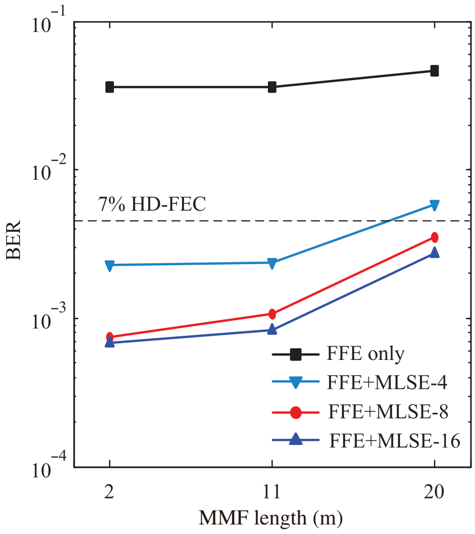


Figure 8 (Color online) BER vs. MMF length (received optical power = 0 dBm).

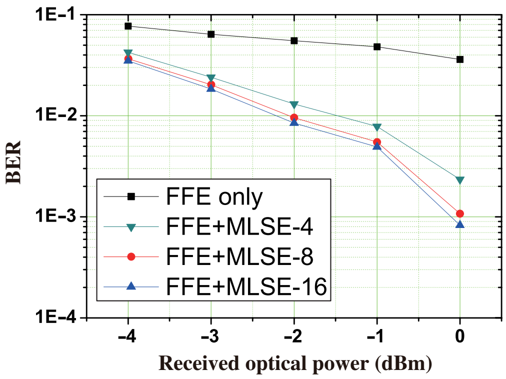


Figure 9 (Color online) BER vs. received optical power (11 m MMF).

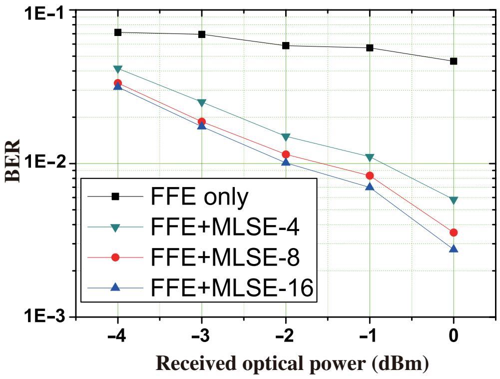


Figure 10 (Color online) BER vs. received optical power (20 m MMF).

signal, in accord with the principle of poster filter.

Figure 8 shows the relations between BER and MMF length under different equalization methods, when the received optical power is 0 dBm. The larger the MMF length is, the higher BER the transmission system will achieve. The results show that the BER rapidly worsens when the MMF lengthens because of the modal dispersion in MMF. In this band-limited system, no matter what the transmission length is, FFE only method cannot reduce the BER lower than 0.03, as a result that FFE+MLSE is essential.

Figure 9 presents the relations between BER and received optical power after 11 m OM4 MMF in different equalization schemes. The FFE-only method cannot recover the signal to a normal level, and the BER is always larger than 0.03. The FFE+MLSE schemes largely enhance the communication quality and are all capable to realize effective data transmission when the received optical power is larger than 0 dBm after using 7% hard-decision (HD) FEC. The 16-state MLSE only brings in slight performance enhancement than 8-state MLSE for BER decrease, and it reduces the BER to 8.28×10^{-4} when the received optical power is 0 dBm.

Figure 10 shows the transmission property for the 20 m OM4 MMF link. Compared with Figure 9, it has similar curve trends, but the communication quality is obviously deteriorated due to the severe modal dispersion in MMF. The FFE only scheme reduces the BER to 0.04 at most, and the FFE+MLSE-4 scheme improves the communication quality to BER of 5.83×10^{-3}. Meanwhile, the FFE+MLSE-8 and 16 scheme decrease the BER to 3.55×10^{-3} and 2.75×10^{-3}, respectively, under the 7% HD FEC, when received optical power is 0 dBm.

4 Conclusion

In this paper, we demonstrate 70 Gb/s (65 Gb/s net rate) NRZ transmission based on an 18 GHz band-limited VCSEL in short-reach optical link. The FFE+MLSE equalization approach helps the system realize effective transmission in at most 20 m OM4 MMF, ensuring BER under 7% HD FEC. The utilized VCSEL is signally cost-efficient and the transmission rate is sufficiently high, showing the enormous potential of the band-limited VCSEL based links in data centers.

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