GaN Light-Emitting Diodes for up to 5.5-Gb/s Short-Reach Data Transmission Over SI-POF

Juri Vinogradov, Roman Kruglov, Kai-Lun Chi, Jin-Wei Shi, Martin Bloos, Sven Loquai, and Olaf Ziemann

***Abstract*— We report a high-speed data transmission over a 1-mm diameter step-index polymer optical fiber (SI-POF) with GaN light-emitting diodes (LEDs) operating at 435 and 475 nm. The modulation bandwidths of the LEDs at 40 mA were 180 and 300 MHz, respectively. A maximum bit rate of 5.5 Gb/s was achieved with a 475-nm GaN LED at −1.8-dBm fiber-coupled power over a 1-m SI-POF employing 4-pulse-amplitude modulation format. Compared with the performance of a high-speed red resonant-cavity LED under the same test setup, the chromatic dispersion reduces the potential of the GaN LED-based system when the transmission distance is longer than 30 m.**

***Index Terms*— Light-emitting diode (LED), polymer optical fiber (POF), pulse-amplitude modulation (PAM).**

I. Introduction

MOST of the actual datacom applications based on step-index polymer optical fibers (SI-POF) operate within the red loss window at the wavelength of 650 nm [1]. However, the green and blue loss windows offer a lower attenuation. Systems operating at short visible wavelengths provide a better tolerance against spectral drift with temperature because of relatively broad attenuation minima.

The recent publications [2], [3] show that bit rates in systems with pulse amplitude modulation (PAM) and GaAs light emitting diodes (LEDs) operating within the red loss window reach 3 Gb/s over a maximum length of 25-m SI-POF. GaN green LEDs can also provide enough modulation bandwidth for gigabit data transmission over POF [4]–[6] employing None-Return-to-Zero (NRZ) and PAM. Furthermore, data transmission over relatively long POF links was successfully achieved using green optical sources. Reliable transmission of a Fast Ethernet data stream over 275 m of SI-POF was realized on the basis of a 520-nm LED [7]. 200 Mb/s NRZ data transmission over 100 m SI-POF using a 509-nm LED was reported in [8]. Besides of optical fiber transmission, free-space Visible Light Communication (VLC) with 512 Mb/s at 520 nm using NRZ was demonstrated in [9]. Results on 1320 Mb/s VLC transmission using carrierless amplitude and phase modulation at a wavelength of 457 nm was published in [10].

Compared with GaAs LEDs used for POF data transmission, GaN LEDs not only have superior dynamic and static performance under high-temperature operation [6], but also might offer lower chip cost due to their application for the solid-state lighting market with tremendous growth in the recent 10 years.

This letter focuses on data transmission over 1-mm diameter SI-POF with GaN LEDs operating at 435 nm and 475 nm. To show a reference level that can be achieved with commercially available components the results on data transmission using a 650-nm resonant-cavity LED (RC-LED) Firecomms FC300R-120 were added to the letter.

II. Description of Data Transmission Setup

The measurement setup consists of the optical transmitter including the GaN LEDs or the RC-LED, SI-POF Mitsubishi GH-4001 with 1-mm core diameter, optical receiver with a silicon pin photodiode having a diameter of 800 μm silicon pin photodiode (Hamamatsu S5052), connected to the transimpedance amplifier with a 3-dB bandwidth of 700 MHz [11]. LEDs were driven over a Bias-T with a modulation index of $m \approx 0.7$. According to the manufactures recommendation the bias current of the GaN LEDs was set to 40 mA, while the RC-LED was operated at 30 mA. To provide a proper level of the modulation signal an additional preamplifier MERA-556+ (Mini Circuits) was used.

An arbitrary waveform generator (Tektronix 7102) was used as a digital-to-analog converter to generate NRZ and 4-PAM signals. The received signal was captured with a real-time oscilloscope (Tektronix DSA71604) and post-processed in Matlab. To compensate non-linear distortions of the 4-PAM signal caused by the LED, a 3rd order Volterra-based equalizer [12] was implemented in addition to a conventional symbol-spaced decision-feedback equalizer (DFE) with 10 linear feed-forward and 10 feed-back taps. The weights of the equalizer were determined using the recursive least squares (RLS) algorithm on the basis of a training sequence [13].

R&D samples of GaN LEDs with a wavelength of 435 nm and an active diameter of 50 μm and a wavelength of 475 nm and an active diameter of 40 μm were used. To improve the coupling efficiency of the LEDs a 500 μm half-sphere lens was mounted on the chip surface [6]. The commercially available 650-nm RC-LED (Firecomms FC300R-120) with 100-μm active area is manufactured in a plastic package and equipped with a molded lens. This device was used as reference to compare the data transmission performance with R&D samples of GaN LEDs.

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J. Vinogradov, R. Kruglov, M. Bloos, S. Loquai, and O. Ziemann are with the Polymer Optical Fiber Application Center, Technische Hochschule Nürnberg Georg Simon Ohm, Nuremberg 90489, Germany (e-mail: juri.vinogradov@pofac.th-nuernberg.de; roman.kruglov@pofac.th-nuernberg.de; martin.bloos@pofac.th-nuernberg.de; sven.loquai@pofac.th-nuernberg.de; olaf.ziemann@pofac.th-nuernberg.de).

K.-L. Chi and J.-W. Shi are with the Department of Electrical Engineering, National Central University, Taoyuan 32001, Taiwan (e-mail: porpoise5233@msn.com; jwshi@ee.ncu.edu.tw).

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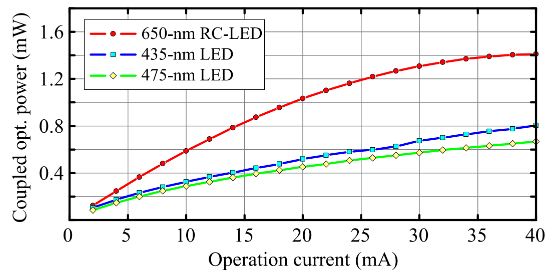

Fig. 1. Fiber-coupled optical power of the LEDs vs. operation current.

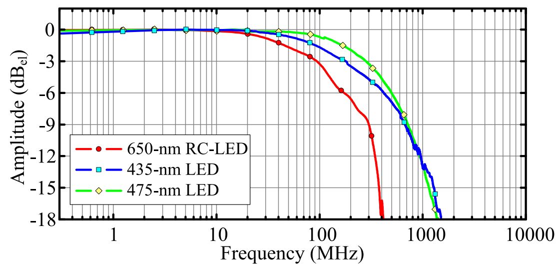

Fig. 2. Normalized frequency responses of the LEDs.

TABLE I
LED PARAMETERS

LED	λ [nm]	Δλ [nm]	$M_0(\lambda)$ [ps/ nm²·km]	Δt at 50 m [ns]
50 µm blue	435	26	1142	1.48
40 µm cyan	475	35	875	1.53
Red RC-LED	650	18	323	0.29

The fiber-coupled optical power of the LEDs P_{opt} shown in Fig. 1 was measured at room temperature after 1-m SI-POF at different operating currents using an integration sphere. The frequency responses of the LEDs were measured with a Graviton SPD-2 optical receiver and an Agilent E5071C network analyzer. Fig. 2 shows the measured electrical-to-optical (E-O) frequency responses. The maximum E-O bandwidths of 180 MHz for blue and 300 MHz for cyan GaN LEDs were reached at 40 mA operating current. The bandwidth of the RC-LED measured at 30 mA is approx. 100 MHz, which corresponds to the data published in [14].

The wide spectral width of the GaN LEDs under test leads to an additional pulse broadening in the SI-POF due to chromatic dispersion including material and waveguide parts. For multimode fibers waveguide dispersion is generally small compared to material dispersion und thus can be neglected [1]. Table 1 shows the important parameters for the calculation of the pulse broadening Δt due to the material dispersion [5], [15].

The pulse broadening Δt [1] was calculated for a link length $L_{POF} = 50$ m and the spectral width $\Delta\lambda$ of the LEDs measured with an Avantes AVASpec 2048 optical spectrometer:

$$\Delta t = M_0(\lambda) \cdot \Delta\lambda \cdot L_{POF},$$

where λ is the wavelength, $M_0(\lambda)$ is the material dispersion parameter.

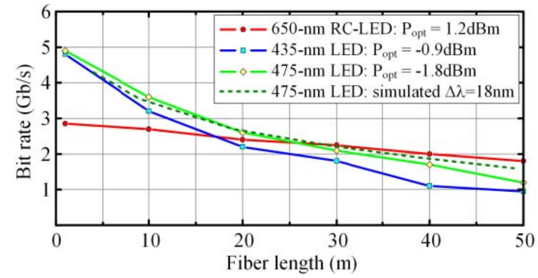

Fig. 3. Maximal bit rates for NRZ modulation scheme over the fiber length achieved at BER of 10^{-3}.

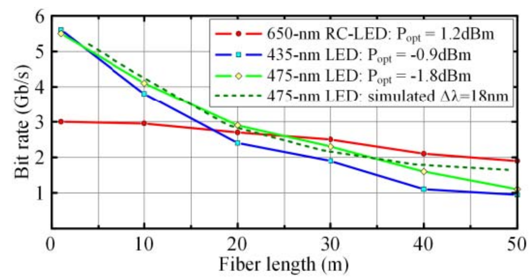

Fig. 4. Maximal bit rates for 4-PAM modulation scheme over the fiber length achieved at BER of 10^{-3}.

As can be seen from Table I, a higher material dispersion at shorter wavelengths can potentially lead to poorer performance at relatively long POF distances.

In order to measure the optical link performance, the LEDs were modulated with NRZ and 4-PAM signals based on pseudo random binary sequence (PRBS 2^7-1). The maximum bit rates determined at BER of 10^{-3} were measured over the fiber lengths from 1 m to 50 m. The mentioned level of BER is sufficient for implementation of the forward error correction. Fig. 3 shows the bit rate versus the POF length using NRZ modulation scheme, while Fig. 4 shows 4-PAM transmission.

Due to the wider E-O bandwidth of the GaN LEDs (180 MHz for 435 nm and 300 MHz for 475 nm) the achieved bit rates at shorter distances (below 20 m) are higher. At longer POF distances not only fiber attenuation and intermodal dispersion, but also a chromatic dispersion has an influence on the performance of the GaN LED-based system. It leads to lower bit rates at 50 m. In contrast to the GaN LEDs, the RC-LED-based system demonstrates a moderate performance at shorter distances. This behavior is caused by the relatively low 3-dB bandwidth of the device (100 MHz), while the 50-m link shows a better performance due to the minor influence of the chromatic dispersion. Thus the bit rate of the RC-LED based system goes down slightly with increase of the fiber length. Bit rates of 3.0 Gb/s and 5.5 Gb/s were achieved over 1-m SI-POF employing 4-PAM modulation format with the 650-nm RC-LED and the 475-nm LED respectively. The 435-nm LED showed a behavior similar to the 475-nm LED, but slightly higher fiber attenuation at 435 nm and limited device bandwidth did not allow to achieve a better performance.

The obvious drawback of the blue and cyan GaN LED is a relatively wide spectral width (see Table 1). To show the potential of short wavelength LEDs for the data transmission over POF an additional simulation with a reduced spectral width was carried out. The green dashed lines in Fig. 3, 4 show

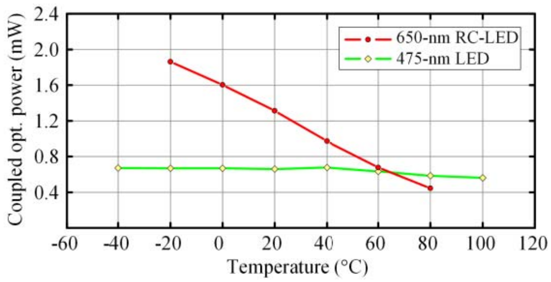

Fig. 5. Dependence of the fiber-coupled power on the temperature for 475-nm LED and 650-nm RC-LED.

the simulated performance of the transmission link employing a 475-nm LED with spectral width of 18 nm, as for the RC-LED. The devices with an optimized spectral width would bring an opportunity to improve the performance of the fiber link. The simulation shows that a maximum bit rate achieved over 50-m SI-POF might be increased by at least 400 Mb/s.

III. Temperature Sensitivity

The capability for high-temperature operation is a key factor for harsh-environment communication. GaN LEDs demonstrate lower temperature sensitivity in comparison with conventional red LEDs. It is explained by that the GaN/InGaN active multiple quantum-wells (MQWs) inside GaN LED has a much larger band offset than that of AlGaInP/GaInP active MQWs layers in the red RC-LED. A higher band offsets can effectively suppress the thermal-induced carrier leakage and improve its performance under high-temperature operation. Furthermore, the high forward bias current density would screen the strong piezo-electric (PZ) field inside GaN/InGaN MQWs and increase the effective barrier height, which would further benefit the high-temperature performance of GaN LED [16].

Fig. 5 shows the change of the fiber-coupled power with temperature for 475-nm LED and 650-nm RC-LED. The fiber-coupled power of the RC-LED decreased by more than 6 dB over the measured temperature range, while that of the 475-nm LED is almost constant.

IV. Conclusion

We tested the performance of 435-nm, 475-nm GaN LEDs and 650-nm RC-LED for gigabit data transmission over SI-POF with 1-mm core diameter. For shorter distances up to 20 m the GaN LEDs under test allow to achieve higher bit rates. A maximum bit rate of 5.5 Gb/s was achieved over 1-m SI-POF employing GaN LEDs and 4-PAM modulation scheme. For longer distances chromatic dispersion worsens the data transmission performance of the GaN LED-based systems. However, using spectrally efficient modulation schemes (e.g. M-PAM [17], or discrete multitone [18]) allows reducing its negative impact. In spite of smaller bandwidth, the RC-LED provides less bit rate reduction up to 50 m for both modulation schemes and demonstrates a better performance over 50 m SI-POF link than the GaN LEDs. Assuming a GaN LED with an output power at room temperature similar to that of RC-LED and reduced spectral width we expect an advantage of GaN LED-based system over a length up to at least 50 m, which becomes even greater for higher operation temperatures.

The performance of these visible range LEDs under different ambient temperature has also been studied. The transmitted optical power of GaN LEDs shows a much better immunity against temperature variation than that of the red RC-LED.

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