

Energy-efficiency of the fiber-optic links based on C-range wafer-fused MBE-grown VCSELs

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The results of studies on the energy efficiency of fiber-optic communication links based on standard single-mode optical fiber ITU-T G.652.D and vertical-cavity surface-emitting lasers in the 1550 nm spectral range, fabricated by wafer fusion and molecular-beam epitaxy, are presented. The fundamental feasibility of reducing the consumed energy per transmitted bit (energy-efficiency), normalized to the communication link length, below 100 fJ/(bit·km) for data transmission at a rate of 10 Gbps over a 10 km fiber-optic link is demonstrated. Further improvement in energy efficiency is constrained by the bandwidth of the fiber-optic communication channel, which is limited by the interaction between the chromatic dispersion of the optical fiber and the dynamic spectral linewidth broadening of the vertical-cavity surface-emitting laser.

Keywords: VCSEL, energy-efficiency, fiber-optic channel.

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Introduction

Fiber-optic transmitters based on 850 nm multimode short-wavelength vertical-cavity surface-emitting lasers (hereinafter referred to as VCSEL) are commonly used for data transfer between neighbour server racks placed in data centers and computer clusters. Such devices are used for high-speed data transmission via the OM4/OM5 multimode optical fiber with a length up to 100 m at a bitrate of 25 Gbps and up to 400 m at a bitrate of 10 Gbps, which ideally suits small and medium computer clusters [1]. However, for further scaling and arrangement of energy-efficient interconnection links, single-mode devices shall be used to reduce the effect of intermodal fiber dispersion. Thus, for short-wavelength single-mode VCSEL, data transmission capability at a distance up to 2 km at a bitrate of 25 Gbps has been demonstrated [2]. As a result, the energy-distance-data ratio (EDDR) has been decreased to 100 fJ/(bit km) [3].

Further increase in the optical data transfer distance via fiber-optic links is only possible when using single-mode optical fiber and O-band or C-band laser emitters, for which the best light propagation conditions are realized: near-zero chromatic dispersion or attenuation less than 0.2 dB/km, respectively [4]. Therefore, the use of long-wavelength O-band or C-band VCSELs for implementing long fiber-optic links has good prospects in terms of their small size, cost and energy efficiency compared with

single-frequency distributed feedback laser with external modulation. Moreover, implementation of compact VCSEL matrices with individual addressing offers new prospects for increasing link bandwidth under the space-division multiplexing technology [5].

Unfortunately, creation of long-wavelength VCSELs is hindered by some fundamental constraints inherent in InAlGaAs/GaAs and InAlGaAsP/InP material systems. To overcome these constraints, the following measures have been proposed and successfully tested: vertical microcavity design with carrier injection through intracavity contacts to reduce free charge carrier loss; buried tunnel junction concept for implementing effective current and optical confinement; hybrid integration of highly reflective distributed Bragg reflectors (DBR) with the active-region realized in InAlGaAsP/InP material system to solve the low heat conductivity problem [6]. VCSEL with hybrid metal-dielectric mirrors (hereinafter referred to as HI-VCSEL) [7,8] and VCSEL with GaAs/AlGaAs semiconductor DBR that were integrated with the active region by wafer fusion (hereinafter referred to as WF-VCSEL) [9]. The above-mentioned approaches are used to implement reliable long-wavelength VCSELs with a –6 dB effective modulation frequency up to 15 GHz [7,9,10]. Note that, though a higher modulation frequency (up to 25 GHz at –6 dB) can be reached within a concept of a short cavity with two high-contrast metal-dielectric mirrors (hereinafter referred to as HI-SC-

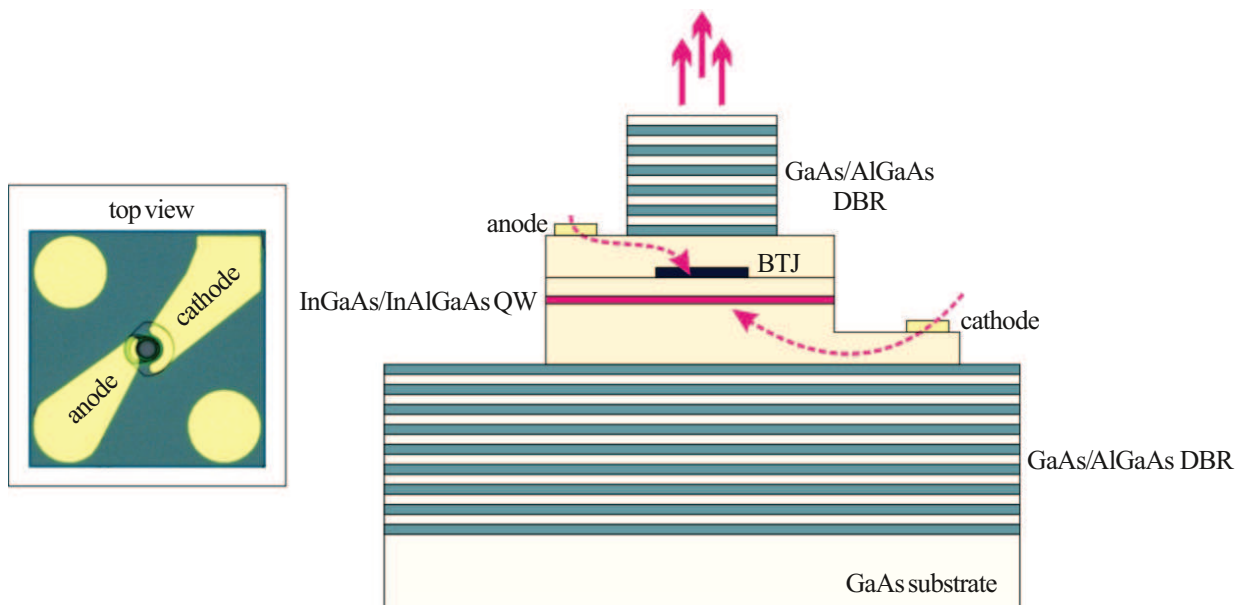


Figure 1. Schematic diagram of a WF-VCSEL structure with a buried tunnel junction (BTJ) and intracavity carrier injection. The inset on the left shows an image of the WF-VCSEL obtained using an optical microscope.

VCSEL) [8], however, reliability according to ITU-Telcordia hasn't been demonstrated for such devices yet.

Due to low O-band fiber dispersion, theoretical capability of data transfer via a fiber-optic link with a length of 10 km at 12.5 Gbps for HI-VCSEL [11], up to 10 km at 35 Gbps for WF-VCSEL [12] and up to 25 km at 28 Gbps for HI-SC-VCSEL [13] has been demonstrated. Integration with a laser driver and *feed forward equalization* technique (FFE) made it possible to increase the data transfer distance to 25 km at 20 Gbps and to 4.5 km at 40 Gbps for HI-SC-VCSEL [14].

Bitrate via long-wavelength C-band VCSELs is limited to a great extent by the fiber dispersion. Thus, for C band, a theoretical capability of data transfer via a fiber-optic link with a length of up to 2 km at 21 Gbps for WF-VCSEL [15] and up to 2 km at 28 Gbps for HI-SC-VCSEL [16] has been demonstrated. The feed forward equalization technique allowed the bitrate to be increased up to 27 Gbps with a link length of 2 km for WF-VCSEL [15]. Additional employment of a *hard-decision forward error correction* (HD-FEC) and *digital signal processing* (DSP) methods allows the data transfer distance to be increased to 10 km at 28 Gbps for HI-SC-VCSEL [16].

As an alternative to digital signal post-processing methods, an approach was proposed where positive dispersion of a 80 km standard single-mode fiber was compensated using an additional 20 km fiber with negative dispersion (*dispersion compensation fiber*, DCF), and was successfully used for data transfer at a distance of 100 km at 10 Gbps [17]. Such solution is suitable for implementing longer links, however, high cost of DCF fiber is the main limitation of this approach.

The object of this study included 1550 nm (C band) WF-VCSELs implemented by a combined molecular-beam epitaxy and wafer fusion method. The study investigated the effect of fiber-optical link length on the data transfer distance and analyzed the energy spent for transfer of one data bit taking into account the length of the ITU-T G.652.D single-mode fiber-optic link. Note that this study used pulse-amplitude modulation without using the feed forward equalization or post-processing techniques, which lead to higher energy consumption.

Objects of study

The test laser structure consists of a hybrid vertical 3λ -microcavity with charge carrier injection through intracavity contacts and lasing into the upper hemisphere. The microcavity is made by fusion of AlGaAs/GaAs DBR wafers and an InAlGaAs/InP active region wafer (Figure 1). Stressed ($\sim 1.4\%$) InGaAs/InAlGaAs quantum wells were used as the active region. Upper and lower DBRs of the studied WF-VCSEL contained, respectively, 22.5 and 35.5 pairs of undoped quarter-wavelength AlGaAs/GaAs layers. The $7\mu\text{m}$ buried tunnel junction was used for creating current and optical confinements. All initial heterostructure growth and tunnel junction regrowth processes were performed by the molecular-beam epitaxy method. For more detailed description of the WF-VCSEL design, see [18].

Figure 2 shows static characteristics of the studied laser. Threshold current of the device is 1.25 mA, series resistance is about 115Ω . At operating currents higher than 2.5 mA, single-mode operation with a side mode suppression ratio (SMSR) more than 30 dB is observed. The output optical

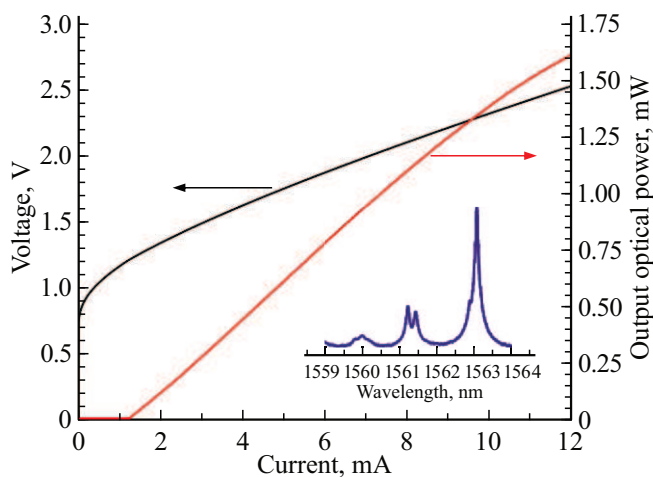


Figure 2. Light-current-voltage characteristics of WF-VCSEL, the inset shows a laser spectrum at an operating current of 12 mA.

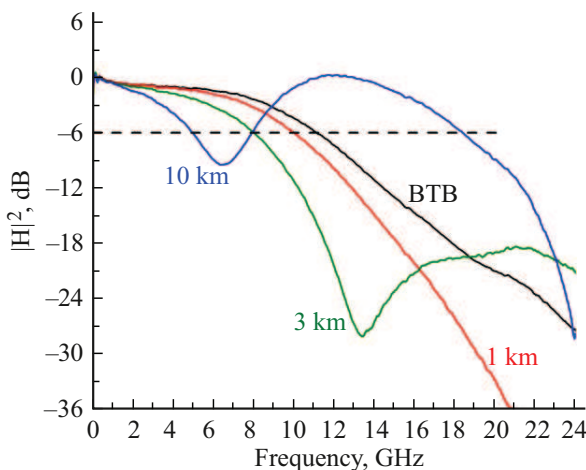


Figure 3. Amplitude-frequency response of the WF-VCSEL and single-mode fiber link with different lengths. Operating current of WF-VCSEL is 12 mA.

power from the single-mode fiber pigtail is no more 1.8 mW, which is due to a relatively low coupling efficiency of 30–40%.

Results and discussion

To evaluate the effect of standard ITU-T G.652.D single-mode fiber length on the WF-VCSEL fiber-optic fiber link bandwidth, amplitude-frequency response was studied by a small-signal analysis. Thus, amplitude-frequency response of the fiber-optic link was measured using the Rohde-Swartz ZVA40 vector network analyzer and Alphalas UPD-15-IR2 fast photodetector, measurement results are shown in Figure 3. For an ultrashort link (back-to-back (BTB) configuration), the optical bandwidth $f_{-3\text{dB}_0}$ (corresponds to the electrical bandwidth $f_{-6\text{dB}_e}$ by the decay level -6 dB measured by the vector network analyzer) is set by the

effective laser modulation frequency and reaches 11.1 GHz. Note that the optical bandwidth of WF-VCSEL effective modulation is essentially limited by two factors: parasitic capacity and mode volume [15,19]. Parasitic frequency of the studied WF-VCSEL is lower than 10 GHz regardless of the optimized layer doping level in the microcavity. Relatively large penetration depth of the mode's electromagnetic field into the semiconductor DBR and the need for using relatively thick intracavity contact layers limit the D-factor and, consequently, the effective modulation frequency. As a result, even when the parasitic frequency increases up to its limits higher than 13 GHz due to mesa topology optimization, the threshold effective modulation frequency is still limited at 15 GHz by -3 dB_0 .

As the fiber length increases, local resonance dips occur on the amplitude-frequency response (the number of dip depends on the frequency range and fiber length), which also shift towards lower frequencies as the fiber-optic link length increases. This is due to interaction between the positive dispersion of the standard single-mode fiber and dynamic broadening of the WF-VCSEL spectral line (previously evaluated α -factor was equal to $\sim 5\text{--}9$ for different instrument modes [18]).

Detailed analysis of the amplitude-frequency response of the fiber-optic link depending on the laser's operating current and link length are shown in Figure 4. At low operating currents (up to $\sim 3\text{ mA}$), the pronounced resonance peak at the WF-VCSEL relaxation oscillation frequency partially compensates the negative effect of resonance decay in the fiber. Increase in the link length leads to a decrease in the rate of the optical bandwidth $f_{-3\text{dB}_0}$ increase (MCEF-factor) and earlier saturation of the current dependence of the $f_{-3\text{dB}_0}$ resulting in more than twofold decrease in the optical bandwidth of the fiber-optic link based on WF-VCSEL and 10 km standard single-mode fiber relative to the BTB configuration.

EDDR of the fiber-optic link can be evaluated as $\text{EDDR} = P_{el}/(BR \cdot L)$, where P_{el} is the laser power consumption; BR is the achieved bit rate; L is the fiber length [3]. Lowest EDDR level can be evaluated from the low-signal frequency analysis data using an expression written as $BR = M \cdot f_{-3\text{dB}_0}$, where M is the spectral efficiency. Real value of M depends on the characteristics of the equipment used for digital optical data transmission analysis, laser packaging, and on the implementation of the feed forward equalization, and can vary in a quite wide range. Therefore, it was decided to use the Shannon–Hartley theorem for a noisy link with a signal transmission quality parameter (Q -factor) of at least 3 and to fix the spectral efficiency at 2 (bit/s)/Hz [20].

Figure 5 shows the measured energy efficiency of the WF-VCSEL fiber-optic link based on WF-VCSEL. Non-return-to-zero modulation on-off keying modulation was used without *feed forward equalization* (FFE), hard-decision forward error correction (HD-FEC) and/or digital signal processing (DSP). The Keysight M8195A generator was used to form input modulation signal, and optical eye

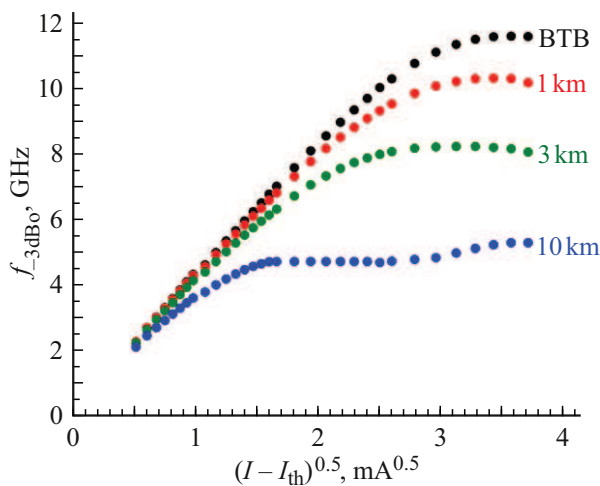


Figure 4. Dependence of the optical bandwidth of the single-mode fiber link with different lengths on the square root of WF-VCSEL current above threshold.

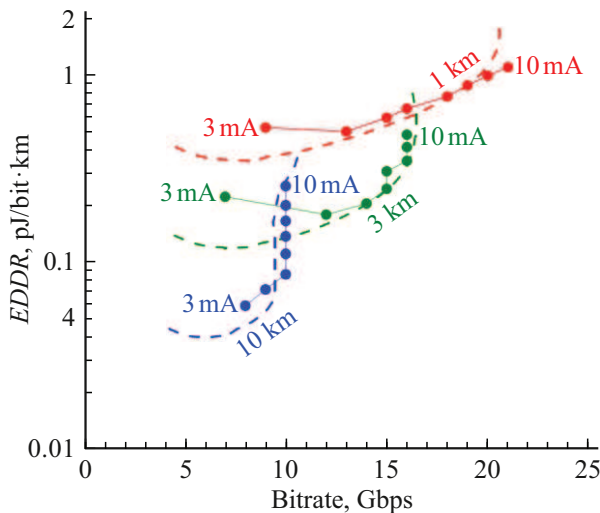


Figure 5. Theoretical energy efficiency (marked by dashed lines) and measured lowest energy efficiency (marked by dots) of the WF-VCSEL fiber-optic link with different bitrates. Measurements were performed for laser's operating current from 3 to 10 mA with 1 mA step.

diagrams were recorded using the Keysight UXR0204A oscilloscope. It is obvious that to reduce EDDR it is necessary not only to increase the speed, but also to reduce the laser power consumption.

According to the theoretical calculation data shown in Figure 5, the lowest EDDR is implemented at intermediate bitrates (5–9 Gbps), which is due to the difference in the MCEF-factor and the power consumption dependencies on the WF-VCSEL operating current. Though an increase in the link length leads to a decrease in the bandwidth, a significant decrease in the minimum achievable EDDR is observed. The maximum bitrate in the BTB configuration exceeds 30 Gbps, which corresponds to the energy efficiency higher

than 1.2 pJ/bit, and a 1.5 times decrease in the operating current leads to a decrease in the energy efficiency to 0.83 pJ/bit [21]. However, a damping shall be considered in this case, because clearly pronounced resonance peaks will lead to intersymbol interference and limit data transfer capabilities without the feed forward equalization techniques. Thus, the adverse effect of relaxation oscillations for the link of interest was suppressed at WF-VCSEL operating currents higher than 4 mA. For a fiber-optical link longer than 1 km, the best EDDR reaches 500 fJ/(bit·km) at a bitrate of 13 bps, which corresponds closely to the theoretical estimates (Figure 5). Note that for a fixed operating current, limitation of the achievable bitrate was observed as the fiber-optical link length increased. Increase in the fiber-optical link length to 10 km limits the bitrate at 10 Gbps, but reduces EDDR to 100 fJ/(bit·km).

Obtained energy efficiencies of the C-band WF-VCSEL fiber-optic link are comparable with the energy efficiency of HI-SC-VCSEL link [16], for which, without using HD-FEC and DSP, data transfer at a bitrate of 28 Gbps via a 2 km fiber-optical link and EDDR equal to ~ 280 fJ/(bit·km) were demonstrated. The obtained energy efficiency of the C-band WF-VCSEL fiber-optic link is also comparable with results of the previous EDDR study of a 2 km WF-VCSEL fiber-optical link where the EDDR values of ~ 600 fJ/(bit·km) were demonstrated [15]. As mentioned above, further decrease in EDDR is possible under the fiber dispersion compensation concept similar to [17].

Conclusion

Thus, this study examined the effect of a fiber-optical link length on the maximum bitrate and energy efficiency of the C-band WF-VCSEL fiber-optical link. Limitation of the optical link bandwidth due to the interaction between the positive dispersion of the standard single-mode fiber and dynamic broadening of the WF-VCSEL spectral line was demonstrated. Evaluated energy efficiencies of the C-band WF-VCSEL fiber-optical link are comparable with the results achieved earlier for an alternative long-wavelength HI-VCSEL design. The demonstrated WF-VCSEL characteristics indicate significant prospects for the implementation of energy-efficient transceivers based on them, designed for high-speed data transmission over fiber communication lines up to 10 km.

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Conflict of interest

The authors declare no conflict of interest.

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