

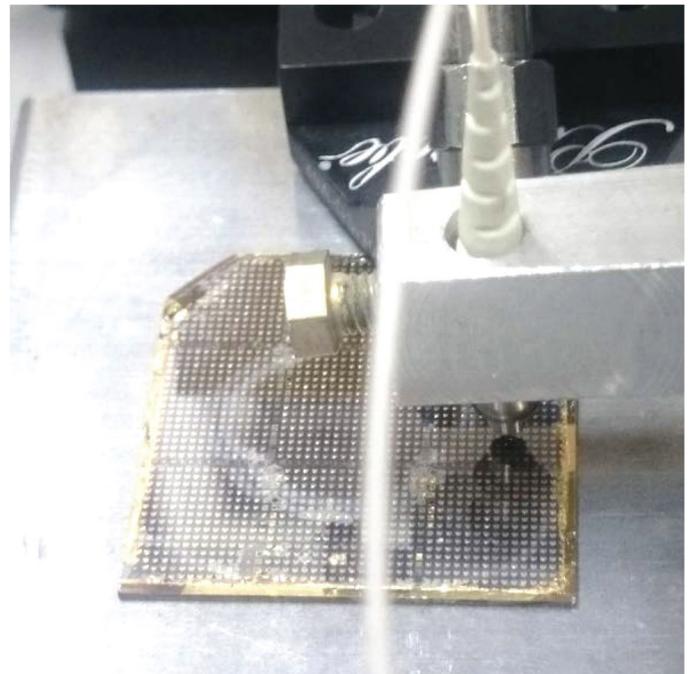
# Short-range links beyond 100Gb/s with vertical-cavity surface-emitting lasers

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*Effective 100Gb/s single-mode optical transmission can be achieved over 100m of multimode fiber by using advanced modulation schemes and digital-signal processing.*

Global data traffic is increasing at an unprecedented rate. This increase is due in large part to the rise of cloud computing services, multimedia web applications, and Internet-of-Things technologies. Indeed, the bandwidth requirements imposed by these applications are expected to double network traffic in data centers within five years.<sup>1</sup> To cope with these demands, the viability of using new photonics technologies and approaches to improve the performance (i.e., to increase the capacity and reduce the latency) of data-center interconnects must be explored. Furthermore, these new approaches must ensure a reduced carbon footprint and lower operating costs.<sup>2</sup>

A large amount of research has recently been carried out on vertical-cavity surface-emitting lasers (VCSELs) with the aim of meeting these requirements. VCSELs represent one of the most appealing technologies for application to optical interconnects because of the advantages that they provide (e.g., low power consumption, reduced fabrication cost, the feasibility of on-wafer testing, and high coupling efficiencies).<sup>3</sup> Additionally, the rapid development of electronics has led to the increased efficacy of advanced modulation techniques over larger bandwidths, thereby significantly increasing the spectral efficiency of communications systems. Combining these new photonics technologies with advanced modulation formats has enabled the development of single-polarization and single-wavelength intensity modulation/direct detection (IM/DD) high-speed links. A number of recent research efforts have achieved effective bitrates of close to 100Gb/s using VCSELs. Specifically, effective bitrates

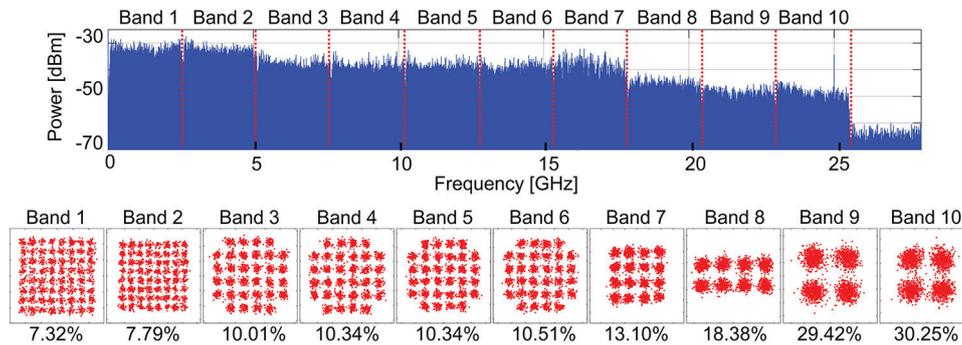


**Figure 1.** Chip wafer of single-mode vertical-cavity surface-emitting lasers (VCSELs), shown together with a fiber-optic pigtail test probe.<sup>7</sup>

of 94Gb/s over 2m of OM4 multimode fiber (MMF) with an 850nm VCSEL, 95.8Gb/s with a 1550nm VCSEL, and 71Gb/s over 7m of OM3 MMF with an 850nm VCSEL were achieved by means of, respectively, four-level pulse amplitude modulation,<sup>4</sup> discrete multitone (DMT) modulation,<sup>5</sup> and non-return-to-zero direct modulation.<sup>6</sup>

By exploiting the versatility of a multiband approach (i.e., carrierless amplitude phase modulation, CAP),<sup>7</sup> we have successfully transmitted an effective bitrate of over 100Gb/s through 100m of OM4 MMF.<sup>8</sup> Multiband CAP modulation provides the

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**Figure 2.** Received electrical spectrum, with corresponding symbol constellations and error vector magnitudes, of all bands after transmission at a rate of 107.5Gb/s. The modulation schemes of the bands range from 64-symbol carrier amplitude phase (64-CAP) modulation to 4-symbol CAP (4-CAP) modulation.<sup>7</sup> For more detail, see Table 1.

**Table 1.** Set of modulation schemes for each multimode fiber (MMF) length tested (i.e., 0, 100, 200, 600, and 1000m) using 2-, 4-, 16-, 32-, and 64-CAP modulation.<sup>7</sup> Data transfer carried out using a VCSEL.

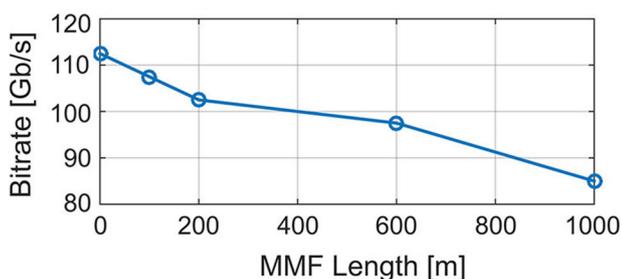
Distance [m]	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10	Bitrate [Gb/s]
0	64-CAP	64-CAP	64-CAP	64-CAP	32-CAP	32-CAP	16-CAP	8-CAP	4-CAP	4-CAP	112.5
100	64-CAP	64-CAP	32-CAP	32-CAP	32-CAP	32-CAP	16-CAP	8-CAP	4-CAP	4-CAP	107.5
200	64-CAP	64-CAP	32-CAP	32-CAP	32-CAP	16-CAP	16-CAP	8-CAP	4-CAP	2-CAP	102.5
600	32-CAP	32-CAP	32-CAP	32-CAP	32-CAP	16-CAP	16-CAP	8-CAP	4-CAP	2-CAP	97.5
1000	32-CAP	32-CAP	32-CAP	16-CAP	16-CAP	8-CAP	8-CAP	4-CAP	4-CAP	2-CAP	85

same advantages that are characteristic of DMT modulation (i.e., bit and power loading), but with a lower peak-to-average power ratio. These features allow the non-flat frequency response of the transmission channel to be mitigated and the spectral efficiency to be maximized. Additionally, as a result of recent developments, single-mode-operation VCSELs are now available (see Figure 1).<sup>9</sup> These enhanced laser sources reduce the transmission impairments that typically arise as a result of intermodal dispersion. As a result of this, their bit-error-rate (BER) performance

is below forward-error-correction (FEC) thresholds, and longer links are achieved.

In our experimental study, we generated a multiband CAP signal consisting of 10 bands—each with a baud rate of 2.5Gbaud—to modulate the 850nm single-mode VCSEL. By employing bit- and power-loading techniques, we assigned modulation schemes to the bands, ranging from a 64-symbol constellation (64-CAP) to a 4-symbol constellation (4-CAP). We carried this assignment out according to the signal-to-noise ratio of each frequency band to ensure a BER below the 7% overhead FEC threshold (i.e.,  $3.8 \times 10^{-3}$ ) for all bands. Figure 2 shows the received electrical spectrum—and the corresponding symbol constellation and error vector magnitude—of each band after transmission over 100m of OM4 MMF.

By adding the bitrate of each band, we calculated that information was transmitted at a total bitrate of 107.5Gb/s. Furthermore, after removing FEC redundancy, we achieved an effective bitrate of 100.47Gb/s. The central frequencies of each band were separated from their neighbors by 2.55GHz, and the first band



**Figure 3.** Maximum total bitrates achieved, below the 7% forward-error-correction threshold, for each MMF length.<sup>7</sup>

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had a central frequency of 1.3125GHz. The total bandwidth occupied by all bands was 25.5GHz, resulting in a spectral efficiency of 4.21bit/s/Hz.

We were also able to increase the resilience of the transmission to optical-link impairments by reducing the modulation order of the bands and, consequently, decreasing the total bitrate. Such a reduction enables longer links to be reached. Using this scheme, we achieved a maximum total bitrate of 112.5Gb/s in back-to-back tests. Furthermore, by decreasing the total bitrate to 85Gb/s, we achieved transmission over 1km of OM4 MMF with a BER below the 7% FEC threshold (see Figure 3). The bitrates that we achieved over different MMF lengths, and the corresponding modulation schemes of all bands, are shown in Table 1.

In summary, we have experimentally validated the feasibility of achieving 100Gb/s short-range links with cost-effective MMF and 850nm VCSELs. The flexibility provided by our multi-band CAP-modulation approach enables transmission rates to be maximized with limited power and bandwidth resources. The advanced digital-signal processing techniques and high-order modulation schemes (i.e., that give rise to rates of over 100Gb/s) are enabled as a result of the increased processing capabilities of today's electronics. In our future work, we will focus on assessing and implementing the necessary analog and digital technologies to enable these high-speed optical links in real time.

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