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# 100G shortwave wavelength division multiplexing solutions for multimode fiber data links

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We investigate an alternative 100G solution for optical short-range data center links. The presented solution adopts wavelength division multiplexing technology to transmit four channels of 25G over a multimode fiber. A comparative performance analysis of the wavelength-grid selection for the wavelength division multiplexing data link is reported. The analysis includes transmissions over standard optical multimode fiber (OM): OM2, OM3 and OM4.

Keywords: vertical-cavity surface-emitting laser (VCSEL), multimode fiber (MMF), wavelength division multiplexing (WDM).

## 1. Introduction

According to Cisco annual global IP report, traffic is increasing by all metrics, and this trend will affect heavily datacenters [1, 2]. Cisco analysis also forecasts that as much as 76% of traffic increment over the next 4 years will remain within data centers [2], where more than 80% of the existing data links are shorter than 100 m [3].

In order to tackle the upcoming need for high capacity links in data centers, 100G standards have already been made available and a task force is finalizing the 400G standards. 100GBASE-SR10 and 100GBASE-SR4 standards propose parallel 10-lanes of 10G and 4-lanes of 25G links using 850 nm vertical-cavity surface-emitting laser (VCSEL) and multimode fibers (MMF) technologies [4]. Figure 1 reports the most relevant features of these two technologies. This upgrade leads to significant investments in data center because it implies changing the number of fibers in the trunk and the patch cables to optical modules.

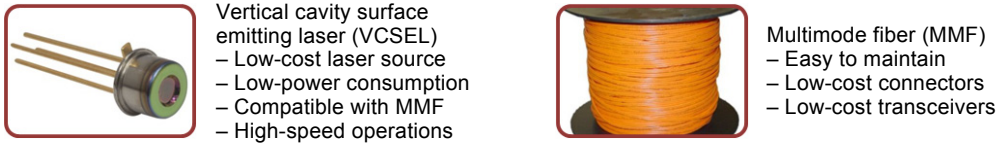


Fig. 1. VCSEL and MMF advantages [4, 5].

This work studies alternative solutions: MMF links that migrate from the standard multiple-fiber-lane approach to single-fiber-lane links by employing wavelength division multiplexing (WDM) of  $4 \times 25\text{G}$  channels.

The proposed WDM solution allows increasing the capacity without adding any extra parallel lane as in parallel optic ones [6]; thus data center providers can continue using their existing MMF infrastructure when upgrading to 100G or 400G. However WDM requires the introduction of a multiplexer (MUX) and demultiplexer (DEMUX), which increase the complexity of receiver and transmitter. Furthermore the modal bandwidth of a standard MMF is a significant limitation when a channel wavelength deviates from 850 nm.

As to reported experimental work, a total capacity of 10 Gbit/s over 300 m MMF was reported by Hewlett–Packard Laboratories and Agilent using  $4 \times 2.5\text{G}$  WDM channels of wavelengths 820, 835, 850 and 865 nm [7]. Transmission at 40 and 100 Gbit/s over a wideband MMF [8] using  $4 \times 10\text{G}$  and  $4 \times 25\text{G}$  WDM links were demonstrated in [9, 10] and the wavelengths grid ranged between 850 and 950 nm. Furthermore the shortwave WDM (SWDM) alliance has been founded with the purpose of developing future SWDM solutions for datacenters [11].

In this paper we further investigate WDM grid solutions located at different regions of the shortwave spectrum. In particular we focus on the limitations introduced by the modal dispersion of the standards optical MMF (OM): OM4, OM3 and OM2 [12].

## 2. WDM short-wavelength over multimode-fiber data link

Figure 2 depicts the scheme of a generic multimode WDM data link, for which we perform a comparative performance analysis. Four signals are transmitted over four

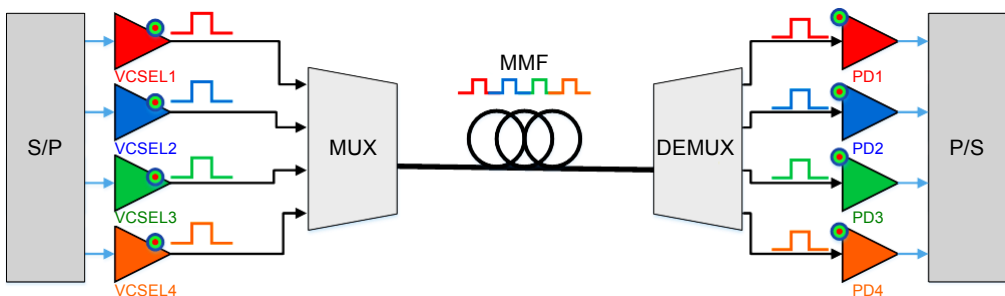


Fig. 1. Schematic diagram of 100G WDM data transmission over MMF.

separate WDM channels (CH1, CH2, CH3 and CH4) at 25 Gbit/s per channel; each channel has its own VCSEL (VCSEL1, VCSEL2, VCSEL3 and VCSEL4) at the transmitter and photodiode (PD1, PD2, PD3 and PD4) at the receiver. The optical MUX merges and DEMUX splits the signals. The WDM grid of the system represents the four wavelengths  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$  and  $\lambda_4$  of the channels.

We selected three WDM grids A, B and C of four wavelengths, which enclose 850, 980 and 1100 nm respectively, where current and emerging VCSEL technology confidently operates at 25 Gbit/s [13–15]. The interchannel spectral separation is fixed to 30 nm according to the standard for coarse WDM (CWDM) [16].

Grid A implements a 100G WDM data link solution compatible with the standard 100GBASE-SR4; in particular the reach requirements over OM4 and OM3. A data link based on grid B is studied to evaluate the possibility to extend the number of channels of a grid A based solution. An emerging solution based on grid C and OM2 is also investigated.

### 3. Computer simulations set up

Computer simulations were performed using commercially available software OptSim™ version 5.2 of Rsoft with its multimode add-on ModeSYS™ [17]. In the OptSim™ environment, optical and electrical components are represented by modules [18]. All the devices modelled in OptSim™ are assumed to operate at an ambient temperature of 25°C.

The simulation set up is presented in Fig. 3 and consists in four WDM channels. The data transmitted through the link is a pseudo-random binary sequence (PRBS) of  $2^{12} - 1$  bits at 25.78 Gbit/s; the bit rate includes the forward error correction (FEC) overhead. Electrical signals adopt on-off-keying (OOK) modulation with non-return-to-zero (NRZ) coding scheme and their voltage peak-to-peak  $V_{pp}$  is set at 1 V.

VCSELs, MMFs, MUX, DEMUX and PDs modules are described in the following subsections. The last module is the bit-error-rate tester (BERT) module, which gathers the BER of an electrical signal.

#### 3.1. VCSEL design

We implemented four OptSim™ VCSEL modules based on real devices: module A [19], module B [20], module C [21] and module D [15]. Table 1 reports the specifications

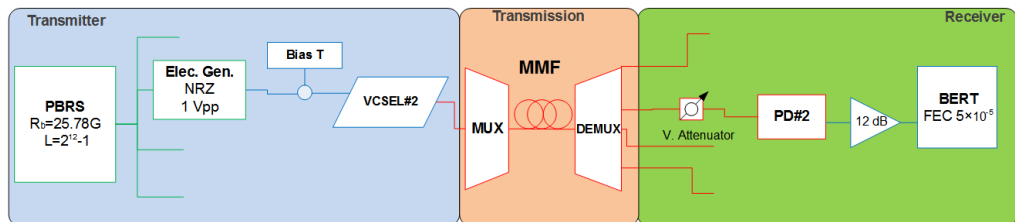


Fig. 3. Simulation set up of a generic WDM channel.

T a b l e 1. VCSEL modules specifications.

Specifications	Module A [17, 20]	Module B [20]	Module C [21]	Module D [15]
Wavelength [nm]	857	982	1060	1100
Bias current [mA]	8.44	12	6	8
Threshold current [mA]	1	0.584	0.45	0.7
Threshold voltage [V]	1.75	1.6	1.2	1.35
3 dB bandwidth [GHz]	12	15	17	15
Differential quantum efficiency	0.25	0.27	0.43	0.36
Linewidth [nm]	0.5	0.5	0.5	0.5
OMA [mW]	2.7	3.1	4.25	2.65
Average power [dBm]	5.1	4.86	5.76	4.35

of the four modules. The reported optical modulation amplitude (OMA) and the average power of the output signal are calculated by the simulator assuming the input electrical signal of the previous section.

Module A has AlGaAs/GaAs DBR mirrors while the other modules have InGaAs ones, which are more feasible and common for VCSELs of wavelengths between 900 and 1020 nm [22]. Therefore we based only the 850 and 880 nm VCSELs on module A, while 910, 940, 970 and 1000 nm on module B, 1030 and 1060 nm on module C, and 1090 and 1120 nm on module D.

### 3.2. MMF design

The modal bandwidth of the fiber is one of the key limiting factors in transmission over MMF [23]. Modal bandwidth stems from the modal dispersion, which depends significantly on the nominal wavelength of the transmitted signal.

We tested three types of fibers: OM4, OM3 and OM2. OM3 fibers are currently the most used in data centers [5], optimized for 850 nm in terms of modal dispersion and appear in the 100GBASE-SR4 standard. OM4 fibers are the most recent MMF and they grant the best performance for the standard 850 nm [24]. In order to complete the analysis, the behavior of the system for a OM2 fiber, which is not optimized for 850 nm, is studied; furthermore OM2 fibers give a more accurate estimation of the potential of the 1060 and 980 nm technologies, where these fibers present their lowest modal dispersion [25]. Table 2 reports the modal bandwidth of OM4, OM3 and OM2 fibers at the channels wavelengths of the three WDM grids. The other specifications of the three fiber modules are taken from [26], in particular those regarding the chromatic dispersion.

### 3.3. MUX and DEMUX design

In the software environment, MUX and DEMUX modules are implemented as a power combiner and splitter with a bandpass filter (BPF) for each channel. The BPFs are centered at their channel wavelengths. The parameters of the optical MUX and DEMUX

Table 2. WDM grids and their modal bandwidth [24, 25].

Wavelength [nm]		MMF modal bandwidth $B_m$ [MHz · km]		
		OM4	OM3	OM2
WDM grid A	$\lambda_1 = 850$ nm	4500	2000	700
	$\lambda_2 = 880$ nm	3300	1750	800
	$\lambda_3 = 910$ nm	2325	1500	870
	$\lambda_4 = 940$ nm	2000	1250	1030
WDM grid B	$\lambda_1 = 970$ nm	1625	1100	1160
	$\lambda_2 = 1000$ nm	1350	875	1345
	$\lambda_3 = 1030$ nm	1200	780	1530
	$\lambda_4 = 1060$ nm	1000	700	1625
WDM grid C	$\lambda_1 = 1030$ nm	1200	780	1530
	$\lambda_2 = 1060$ nm	1000	700	1625
	$\lambda_3 = 1090$ nm	750	625	1630
	$\lambda_4 = 1120$ nm	625	575	1570

Table 3. MUX and DEMUX parameters.

Bandwidth [nm]	Insertion loss [dB]	Minimum isolation [dB]	BPF type	BPF order
20	0.5	14	Lorentzian	2

are reported in Table 3. These parameters are derived from two real coupler based MUX and DEMUX [27, 28]; the minimum isolation of the filter is measured at the neighbour channels.

### 3.4. PD design

Each channel has an optical receiver composed by PD, transimpedance amplifier (TIA) and electrical low-pass filter (LPF) (see Table 4) [18]. Two optical receiver modules: PD-D30 and PD-R40 are implemented and based on [29] and [30], respectively. The thermal noise of the TIA is represented as a power series expansion of frequency [18].

The input optical power of the PD is regulated by an attenuator. At the receiver output of PD-30 and PD-R40 electrical power amplifiers of 26 and 12 dB, respectively, are introduced.

Table 4. PD-TIA filter specifications.

Specifications		PD-D30 [29]	PD-R40 [30]
PD	Operating wavelength	700–890 nm	900–1350 nm
	Quantum efficiency	0.58 (850 nm)	0.47 (1310 nm)
	Dark current	10 pA	10 pA
	TIA Impedance $Z_T$	6.5 $\Omega$	100 $\Omega$
LPF	3 dB bandwidth	30 GHz	30 GHz

### 3.5. Optical power budget

Table 5 reports the optical power budget of four WDM channels. We selected a channel for each VCSEL module: 850 nm for module A, 970 nm module B, 1030 nm module C and 1120 nm module D. The fiber attenuation is calculated at 100 m, which is the maximum required distance by the standards.

## 4. Simulation results

Simulation results are presented as BER curves:  $\log(-\log(\text{BER}))$  versus the received optical power by the PDs. BER is calculated through the overlap integration of the noise distributions per symbol, which were estimated with the Monte Carlo technique of OptSim™ [18]. The FEC threshold is  $5 \times 10^{-5}$  [31], and the receiver BER operating limit is set to  $10^{-9}$ , which we adopt as an error free threshold.

### 4.1. Grid A

Figure 4 shows the BER curves of the grid A for transmissions over back-to-back (B2B) and 100 m OM4. The four channels achieve BER values lower than  $10^{-9}$ . In the B2B scenario, VCSEL3 and VCSEL4 have larger bandwidth than the other two VCSELs; therefore CH3 and CH4 achieve a lower BER. In the 100 m OM4 scenario, because the modal bandwidth is maximal at  $\lambda_1 = 850$  nm, CH1 performs the best while CH4 at 940 nm the worst.

BER curves over OM3 in Fig. 5 show similar results to the OM4 case: in B2B CH4 has the best performance and CH1 the worst; although the penalization introduced by the fiber modal bandwidth reverses the situation. Simulation results show that error free transmissions at 50 m OM3 are doable.

### 4.2. Grid B

Simulation results shown in Fig. 6 confirm that the four channel of grid B can achieve error free transmissions (BER lower than  $10^{-9}$ ) over 50 m of OM4.

As in the previous case, in the B2B scenario CH3 and CH4 achieve lower BER because VCSEL3 and VCSEL4 have larger bandwidth [18, 19]. However the intro-

Table 5. Power budget over 100 m MMF.

		Channel wavelength			
		850 nm	970 nm	1030 nm	1120 nm
VCSEL	Output optical power [dBm]	+5.1	+4.86	+5.76	+4.36
MUX	Insertion loss [dB]	-0.5	-0.5	-0.5	-0.5
MMF	Attenuation [dB/km]	-2.2	-2	-1.5	-1
	Connector losses [dB]	-1	-1	-1	-1
DEMUX	Insertion loss [dB]	-0.5	-0.5	-0.5	-0.5
Total losses over 100 m [dBm]		-2.22	-2.2	-2.15	-2.1
Receiver	Input optical power [dBm]	+2.88	+2.66	+3.16	+2.26

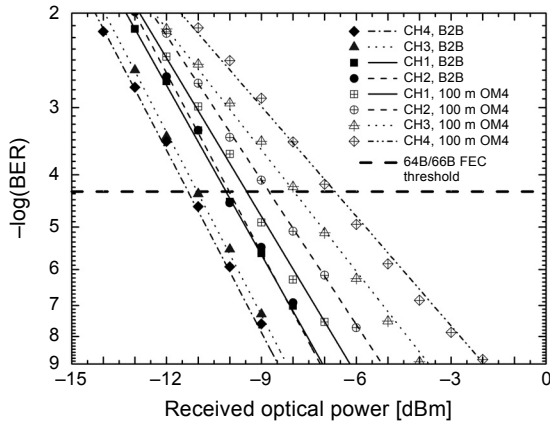


Fig. 4. WDM grid A BER curves over OM4.

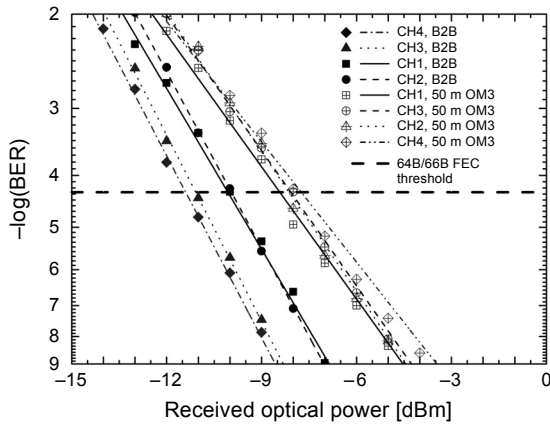


Fig. 5. WDM grid A BER curves over OM3.

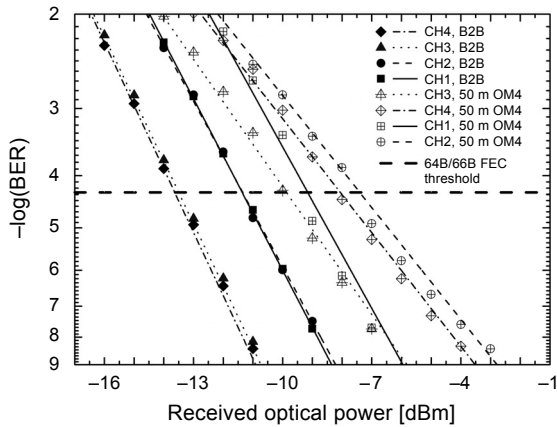


Fig. 6. WDM grid B BER curves over OM4.



duction of the 850 nm optimized OM4 penalizes the four channels; thus the reach is significantly reduced compared to the grid A. Only CH1 can transmit at 25.78 Gbit/s over 100 m OM4 keeping the BER below the FEC threshold.

### 4.3. Grid C

BER curves presented in Fig. 7 show that data transmissions over 100 m OM2 are attainable for all the channels. CH1 (1030 nm) has the narrowest modal bandwidth of 1530 MHz·km; however in B2B CH3 and CH4 perform worse than CH1 because of the narrower bandwidths of VCSEL3 and VCSEL4 [10, 11].

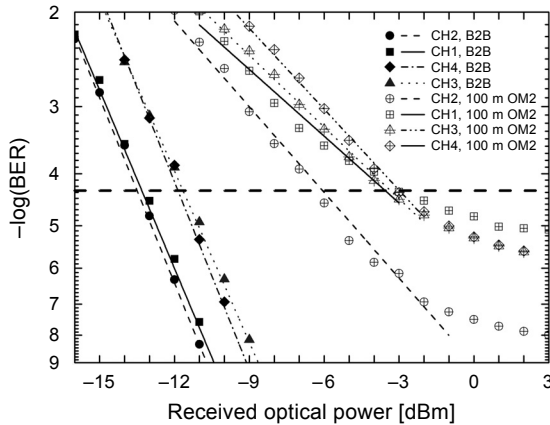


Fig. 7. WDM grid C BER curves over OM2.

In the 100 m case BER curves of the four channels present error floors. The cause is the modal bandwidth of the fiber, which at 100 m becomes narrow enough to introduce intersymbol interference (ISI) independent of from the optical power.

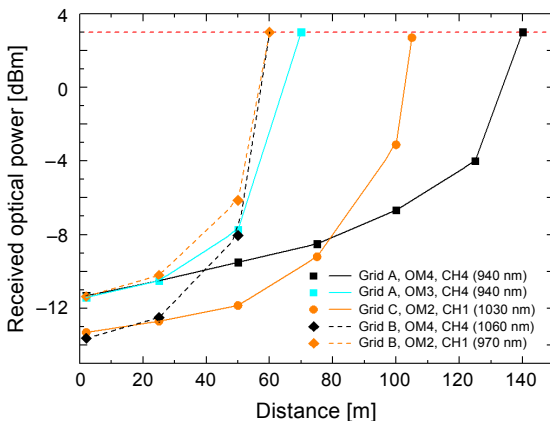


Fig. 8 Required optical power at FEC threshold *versus* distance.

#### 4.4. Results analysis

The curves in Fig. 8 represent the power at BER equal to the FEC threshold as a function of the MMF length. The horizontal dashed line depicts the maximum power tolerated by the PDs (3 dBm).

In Figure 8 we consider the worst channel for each grid, hence the one with the highest modal dispersion for the tested types of MMF. Grid A and C can afford 100 m of OM4 and OM2 with an optical power around  $-5$  and  $3$  dBm, respectively. Grid A reaches 70 m OM3, even if CH4 has BER almost at the FEC threshold.

Table 6. Reach limitations of the three WDM grids.

	Fiber	Worst channel	FEC maximum reach [m]	BER $< 10^{-9}$ maximum reach [m]
Grid A	OM4	CH4 (940 nm)	140	115
	OM3	CH4 (940 nm)	70	50
Grid B	OM4	CH4 (1060 nm)	60	50
	OM2	CH1 (970 nm)	60	50
Grid C	OM2	CH1 (1030 nm)	105	80

Table 6 reports for each WDM grid the maximum OM4, OM3 and OM2 length, which grants a BER lower than the FEC threshold at 25.78 Gbit/s per channel.

## 5. Conclusion

In this paper, we report on numerical simulations for 100G transmissions over a single MMF data link using short-wavelength WDM. WDM grids ranging from 850 to 1120 nm and using OM2, OM3, and OM4 fibers are tested in order to study the transmission distance limitations due to modal dispersion.

Simulation results confirm that grid A, which include the standard 850 nm, is a valid 100G solution for OM4 and OM3 data links. The system satisfies the distance requirements of the 100GBASE-SR4 standard: 100 m for OM4 and 70 m for OM3.

On the other hand, grid B can reach 100 m OM4 only in CH1, although the adjacent channels can grant error free transmissions over 50 m OM4. Therefore an eventual expansion of the first grid is not an optimal solution for data center links.

Moreover, WDM grid C allows transmission over 100 m of OM2. This result rehabilitates the obsolete OM2 technology that is disappearing from data centers [5] and is not required by any new standard.

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