Active Demultiplexer-enabled Directly Modulated DMT Transmission Using Optical Frequency Combs for Data Center Interconnects

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***Abstract*—In this paper, we experimentally demonstrate an optical frequency comb (OFC) based transmitter, employing directly modulated active demultiplexers, for data center interconnects. The results validate that the proposed transmitter has the potential to achieve aggregate data rates of 100 Gb/s (8 × 12.5 Gb/s) and 200 Gb/s (8 × 25 Gb/s) for systems employing 4- and 16- quadrature amplitude modulated (QAM) discrete multi-tone (DMT) modulation. An OFC based on an externally injected gain switched laser (EI-GSL) is used, providing excellent stability and flexibility in free spectral range (FSR). The OFC is followed by an injection locked active demultiplexer, which not only filters, but also amplifies individual comb tones, thus alleviating the need for an external optical amplifier to boost the low powered comb tones. Using the proposed configuration, we experimentally demonstrate a successful transmission of 12.5 Gb/s/λ 4-QAM DMT and 25 Gb/s/λ 16-QAM DMT signals over 40 km and 25 km of SSMF, respectively. In addition, we show that it is possible to filter and modulate comb lines that are 20 dB below the spectral peak, whilst achieving a BER below the hard decision (HD-) FEC limit of 3.8e-3. This gain flattening or comb expansion feature leads to a significant increase in the channel count, which in turn provides a reduction in the energy consumption and the footprint of the transmitter.**

***Index Terms*—Active demultiplexer, data center interconnects, direct modulation, discrete multi-tone, optical frequency combs.**

I. INTRODUCTION

OVER the past decade, the global demand for communication capacity has increased exponentially [1]. This enormous growth in data traffic, caused predominantly by the bandwidth-hungry applications, like cloud computing and new web applications, is driving data center networks (DCNs) to the so-called “Zettabyte threshold”, as predicted by a Cisco report [2]. As a result, there is an increasing need for high-speed DC interconnects (DCI) [3], [4]. To meet the growing demand for bandwidth, DCNs must evolve towards higher performance and throughput, whilst improving the spectral efficiency (SE) and reducing the power consumption [5]. A viable solution is to use coherent-detection based transmission, but it brings about a significant increase in the system complexity and cost [6]. An attractive alternative is to use intensity modulation and direct-detection (IM/DD) based techniques, such as four level pulse amplitude modulation (PAM4) and discrete multi-tone (DMT) modulation. Currently, 100 Gb/s and 400 Gb/s transceivers, based on quad small form-factor pluggable (QSFP28), and QSFP-double density (QSPF-DD) are deployed. Their typical power consumption ranges from 3.5W to 12W [7]–[9] and their transmission lengths range from few meters to 40 km. The QSFP28 consist of 4 channels, each modulated with a 25Gb/s NRZ signal (IEEE 802.3ba 100GBASE). The QSFP-DD consists either 8 or 4 channels of 53 Gb/s (IEEE 400GBASE-FR8), and 106 Gb/s PAM 4 (IEEE 400GBASE-DR4) signals, respectively [9].

The DMT technique can be advantageous in DCIs, as it offers high SE. Furthermore, the use of DMT is advantageous because we could use RF filters to reduce any interference that may occur from the optical demultiplexer stage at the receiver. Moreover, the transmission of multiple data streams, using wavelength division multiplexing (WDM), allows scaling of the optical interconnect density in DCNs. To further enhance the SE and facilitate increasing of capacity, dense WDM (DWDM) and a higher channel count could be used. Recent work on WDM interconnects, clearly shows that the most commonly employed transmitters comprise an array of on-chip laser sources. The authors in [10], demonstrated a 2 × 56 Gb/s PAM4 transmission over 100 km standard single mode fiber (SSMF) using directly modulated lasers. Another impressive demonstration, reported in [11], entailed a four channel 50 Gb/s DMT signal transmission for short reach networks. While an array of laser sources with large channel spacing ($\sim$ 1 nm) enabled these notable

Manuscript received February 2, 2021; revised May 12, 2021; accepted June 21, 2021. Date of publication June 23, 2021; date of current version September 13, 2021. This work was supported by Science Foundation, Ireland, under Grant 15/CDA/3640, by the DTIF under Grant DT20180268, and by SFI/European Regional Development Fund under Grants 13/RC/2077 and 18/SIRG/5579. *(Corresponding author: Syed Tajammul Ahmad.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2021.3091959.

Digital Object Identifier 10.1109/JLT.2021.3091959

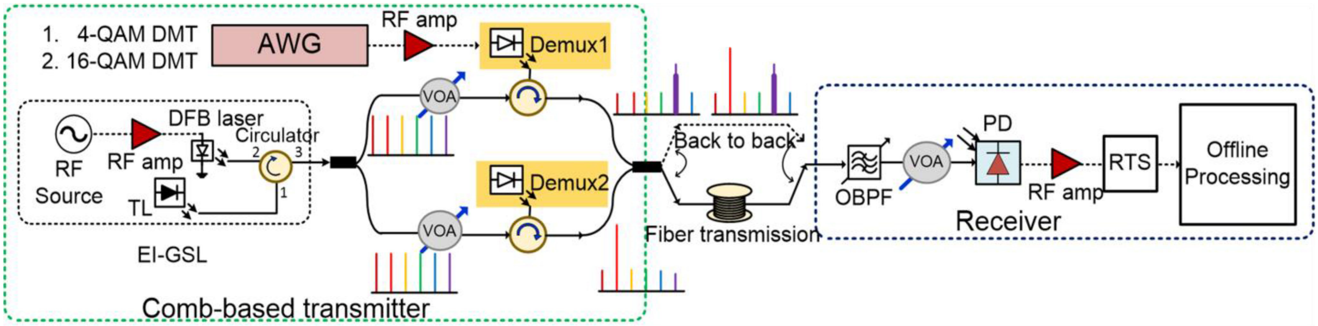


Fig. 1. Experimental setup of the proposed active demultiplexer based M-QAM DMT transmission system using EI-GSL based OFC. Here AWG—arbitrary waveform generator; EI-GSL—externally injected gain switched laser; TL—tunable laser; VOA—variable optical attenuator; OBPF—optical bandpass filter; PD—photodetector; RF amp—radio frequency amplifier; RTS—real time oscilloscope.

demonstrations, it limits the scalability, worsens the energy efficiency and increases the cost of transceiver design.

OFCs are considered a promising alternative to a laser array, as sources for DCIs, due to their ability to provide denser channel spacing [12], [13]. The use of an OFC enables simple and cost-efficient generation of tones that exhibit precise wavelength spacing and portray a high degree of phase correlation between the comb tones. The precise spacing allows the reduction of the size of frequency guard bands, hence guarantee better SE. One of the OFC generation techniques, that can readily provide these features, is the externally injected gain switched laser (EI-GSL) [14]. While OFCs provide several advantages, they suffer from low comb line power (CLP), which is worsened by the insertion loss of a passive demultiplexer, required to separate the carriers/comb tones prior to data modulation. As a result, an external optical amplifier is required to enhance the CLP, at the cost of degrading the optical signal to noise ratio (OSNR), due to amplified spontaneous emission noise. To overcome this drawback, an active demultiplexing technique based on optical injection locking (OIL) has been widely researched [15]. A detailed characterisation of such a scheme is reported in [16] and a demonstration of the multifunctionality of the demultiplexer (its ability not only to filter, but also amplify and serve as a modulator), is discussed in [17], [18].

In this paper, we experimentally demonstrate an OFC based transmitter, employing 4-and 16-QAM DMT modulation formats, in conjunction with the proposed active demultiplexers. It is important to note that our proposed scheme can work with any OFC source (microcombs, mode locked based combs, electro-optic combs etc.). In our demonstration, we use an EI-GSL based OFC, because of its simplicity and FSR tunability. We also show that, thanks to the unique properties of the demultiplexer, it is possible to filter and modulate comb lines that are 20 dB below the spectral peak, whilst achieving a bit error rate (BER) below the HD-FEC limit of 3.8e-3. As a result, the number of comb tones (WDM carriers) that can be used for the data transmission are substantially increased, leading to a significant reduction in energy consumption and footprint of data center transceiver. In addition, we show the successful transmission of 12.5 Gb/s/λ 4- and 25 Gb/s/λ 16-QAM DMT signals, using the proposed transmitter, over 40 km and 25 km of SSMF, respectively. By utilizing the comb tones with power 20 dB below the spectral peak, using a single EI-GSL OFC, the proposed system has the potential to achieve the aggregate data rates of 100 Gb/s (8 × 12.5 Gb/s) and 200 Gb/s (8 × 25 Gb/s) for 4- and 16-QAM DMT respectively. It is important to note that the proposed transmitter configuration lends itself to photonic integration, which can be used to realize a reduced form factor [19].

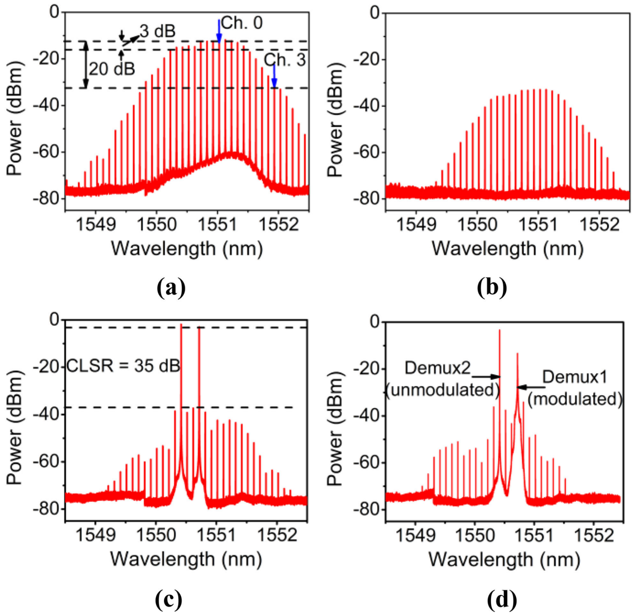
II. Principle and Experimental Setup

The experimental set-up of the proposed directly modulated active demultiplexer based transmitter, is shown in Fig. 1. At the transmitter, an EI-GSL generates an OFC with an average power of 6 dBm and an FSR of 12.5 GHz [14]. The output of the OFC is split using a 50:50 coupler and injected, via circulators, into two semiconductor lasers, acting as active demultiplexers. For this demonstration, as the demultiplexers we used two commercially available distributed feedback (DFB) lasers, with threshold currents (I_{th}) of ∼12.5 mA. The lasers are biased at 4 times I_{th} (∼51 mA) and emit approximately 9 dBm of average optical power. The demultiplexing is achieved by aligning the wavelength of the demultiplexer with one of the comb lines, thereby injection locking the DFB with the desired comb tone. The injected comb line power (CLP) is set, using inline variable optical attenuators (VOAs), to -27 dBm (for lines within 3 dB from the spectral peak) and -35 dBm (for lines 20 dB below the spectral peak), to yield a comb line suppression ratio (CLSR) of 35 dB for both the cases. We define CLSR as the power difference between the filtered comb tone and the remaining unsuppressed lines [17]. Since the proposed demultiplexing technique is based on a passive splitting of the comb output, the attenuation values (at the inline VOAs: 28 dB (tones 3 dB from the spectral peak) and 20 dB (tones 20 dB below the spectral peak)) can be considered as the power budget determining the maximum split ratio. Hence, with an attenuation of 28 dB and 20 dB, a split ratio of 1:512 and 1:64 [20], could be realised, whilst ensuring that stable injection locking and an optimum CLSR are attained. Thus, the same comb could be used as an input to many demultiplexers within the system, ensuring reduction in cost and complexity. It is also important to note that the power difference between the input CLP and the output of the demultiplexer indicates that the active demultiplexer acts not only as a filter, but also as an amplifier. In this case, the active demultiplexer provides a gain of 36 dB and 45 dB, respectively for comb tones within 3 and 20 dB from the spectral peak, calculated by comparing the injected CLP with that of the demultiplexer output (9 dBm).

Another key advantage, in using a commercially available standard semiconductor laser as an active demultiplexer, is that it can be directly modulated with data, thus eliminating the need for an external modulator. In this paper, we demonstrate a proof-of-concept experiment, where 4- and 16-QAM DMT data signals are used to modulate a single active demultiplexer at a time (due to equipment limitations). As in Fig. 1, we modulate demultiplexer 1 (Demux1) with a 40 mA peak to peak data signal, while the other demultiplexer (Demux2) is left unmodulated. The DMT signal is synthesized offline in Matlab and generated using a Keysight arbitrary waveform generator (AWG) operating at 60 GSa/s. The data signal consists of 112 M-QAM subcarriers ($M = 4$ and 16), with a subcarrier spacing of 55.2 MHz. A cyclic prefix of 6.25% is added to overcome the inter symbol interference (ISI) among DMT symbols. A total of 500 DMT symbols are transmitted, amongst which 30 are used as training symbols for receiver synchronization and post equalization. Each DMT symbol occupies an overall bandwidth of 6.625 GHz, thus giving a raw (actual) data rate per channel of 13.25 Gb/s (12.5 Gb/s) and 26.5 Gb/s (25 Gb/s) for 4- and 16-QAM signals respectively. As this is a proof-of-concept demonstration, the achieved data rate can be further improved by optimizing the signal bandwidth and the FSR of comb. The combined demultiplexer's output, with an average optical launch power of 8.6 dBm, is then transmitted over SSMF. At the receiver, the modulated signal is filtered using an optical bandpass filter (OBPF) with a 3-dB bandwidth of 28 GHz. A VOA is used to vary the received optical power (ROP) falling on a 20 GHz Thorlabs PIN photodetector (DXM30AF). Subsequently, the signal is electrically amplified and then captured using a real-time oscilloscope operating at 100 GSa/s. Finally, the offline processing (re-sampling, timing synchronization, phase estimation and BER measurements) is performed in Matlab.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The optical spectrum of the OFC with an FSR of 12.5 GHz is shown in Fig. 2(a). It consists of 12 and 24 comb tones within 3 dB and 20 dB from the spectral peak, respectively. Conventionally, while using passive demultiplexers, only 12 tones with powers within 3 dB from the spectral peak would be used for data transmission. This ensures a near uniform performance across all the channels. However, with the proposed multifunctional demultiplexer, data can be successfully transmitted using comb lines that are 20 dB below the spectral peak. This stems from the fact that, as long as the comb tone has sufficient power to achieve the injection locking of the demultiplexer, the power of the filtered tone at the output of the demultiplexer will remain constant (equal to the output power of the demultiplexing laser). This feature, together with the tunability of the comb FSR, means that the proposed transmitter offers an enhanced channel count and scalable data rates. Fig. 2(b) shows the spectrum of the OFC injected into the demultiplexer after the VOA (attenuation = 28 dB). Fig. 2(c) shows the combined output of two demultiplexers, filtering tones separated by 37.5 GHz and achieving a CLSR of 35 dB. This channel spacing is specifically chosen to avoid any interference between the adjacent WDM channels that are directly modulated (double side band) with the 6.625 GHz DMT signal. Fig. 2 (d) shows the spectrum of the combined output of the modulated Demux1 and the unmodulated Demux2. As mentioned earlier, the active demultiplexer amplifies the filtered line with a gain equal to the difference in power of the injected and the demultiplexed tones, as depicted by the spectra in Fig. 2(b) and (c).



(a) (b) (c) (d)

Fig. 2. Optical spectra showing (a) OFC with 12.5 GHz FSR after EI-GSL block shown in Fig. 1, (b) OFC injected into the active demultiplexer after VOA, (c) two unmodulated comb lines, and (d) two demultiplexed comb lines with one modulated with DMT signal. The optical spectra are recorded using an OSA with 20 MHz resolution and with a fixed 10 dB optical attenuator at its input.

Fig. 3 shows the superposition of 8 DWDM channels (Ch. -4 to Ch. 3), which can be used for data modulation to achieve an aggregate data rate of 100 Gb/s (8 × 12.5 Gb/s) for a 4-QAM DMT and 200 Gb/s (8 × 25 Gb/s) for a 16-QAM DMT system. As mentioned earlier, a 37.5 GHz spacing between the DWDM channels is used to avoid inter-channel interference. However, the aggregate data rate (and SE) of the system can be increased, by optimizing the bandwidth of the DMT signal and the FSR of the comb, in order to utilize all the available comb lines within 20 dB from the spectral peak.

To evaluate the system performance, BER measurements versus ROP are carried out for three different transmission cases: i) back-to-back (BtB), ii) 25 km, and iii) 40 km SSMF transmission. The performance is further evaluated, by modulating two different comb lines, as indicated by the blue arrows in Fig. 2(a): Ch. 0 and Ch. 3.

A. 4-QAM DMT System

The BER vs ROP plots for the three transmission cases (0, 25 and 40 km) are shown in Fig. 4(a). In this plot, the performance of

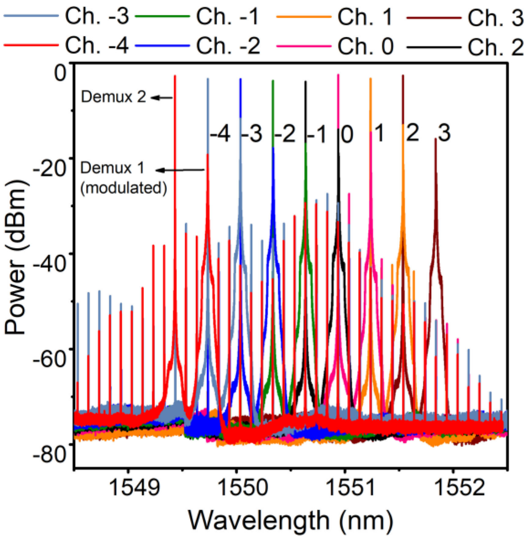
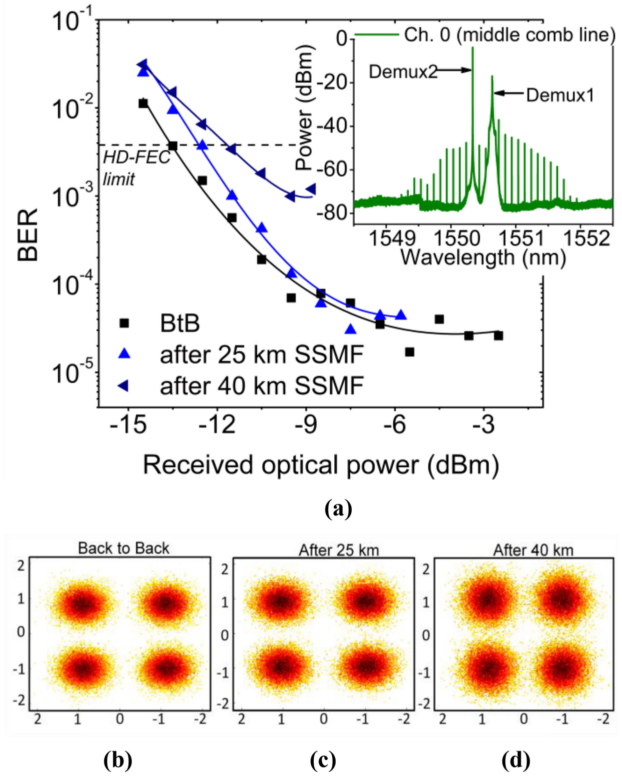


Fig. 3. Optical spectra showing superposition of 8 DWDM channels within a bandwidth of 2.4 nm, each modulated with M-QAM DMT signals. OSA resolution: 20 MHz, fixed optical attenuation at the input of the OSA: 10 dB.



(a)

(b) (c) (d)

Fig. 4. (a) BER vs received optical power for back-to-back, 25 km and 40 km of fiber transmission. The inset shows the spectrum of the directly modulated Ch. 0 combined with a second demultiplexed line 37.5 GHz away. Constellation diagrams at received optical power of -9.5 dBm for (b) back-to-back, (c) 25 km and (d) 40 km transmission.

the Ch. 0 directly modulated with 4-QAM DMT data is shown. The inset in Fig. 4(a) shows the combined output spectra of the Ch. 0 modulated with data (Demux1) and an unmodulated line (Demux2).

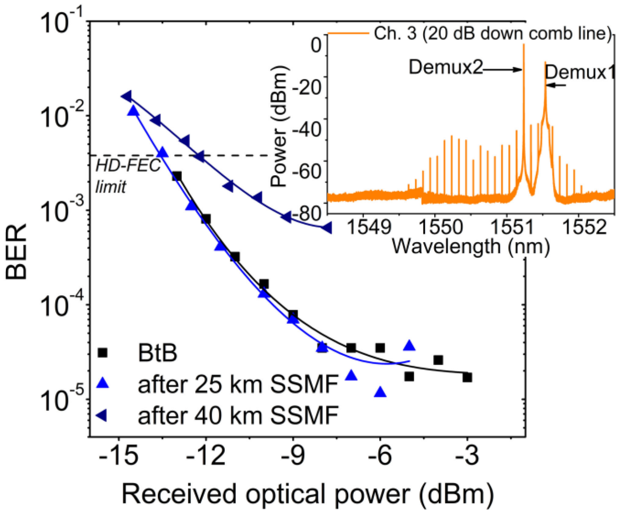


Fig. 5. BER vs received optical power for BtB, 25 km and 40 km of fiber transmission. The inset shows the spectrum of combined demultiplexer outputs with directly modulated demultiplexer (Demux1) injection locked with the Ch. 3.

An improvement in the BER with an increase of the ROP, is observed for the BtB and 25 km transmission cases, until it reaches −6 dBm. Beyond that value, the PD saturates, and the nonlinearities start to degrade the performance of the system. The performance for the 40 km transmission is limited mainly by the receiver noise (leading to a noise floor), as the maximum ROP is restricted to -8.8 dBm by fiber attenuation. From Fig. 4 it can be seen that, at the HD-FEC limit, the fiber transmission introduces a power penalty (compared to BtB) of 0.8 and 2 dB for 25 and 40 km respectively. This can be attributed to the interference caused by the unsuppressed comb tones. As these unsuppressed lines pass through the Demux1, they are modulated with the data. As a result, both the demultiplexed tone and the spurious lines are modulated with the same DMT signals. When transmitted over fiber, chromatic dispersion causes a phase mismatch between all these data signals. At the receiver, the unsuppressed tones that pass through the OBPF, are detected on the photodiode, producing an interfering signal falling in band with the data. The impact of this interference can be reduced, by reducing the injection power (CLP). However, it is important to note that there is a trade-off between the improved CLSR and the injection locking range, thus the stability of the demultiplexing process [13]. The Figs 4(b), (c) and (d) show the constellation diagrams for 4-QAM DMT system, at an ROP of -9.5 dBm, for the BtB, 25 km and 40 km fiber transmission respectively. From the constellation diagrams, it is clear that a significant amount of noise is present in the symbols with transmission over 40 km SSMF (Fig. 4(d)).

The BER performance of the directly modulated Ch. 3 is also evaluated and illustrated in Fig. 5. The inset shows the combined spectra of the two demultiplexers, when Demux1 is injection locked by Ch. 3. The plot shows the presence of a negligible power penalty, at the HD-FEC limit, for the 25 km transmission case. For the 40 km transmission case, a penalty of 1.6 dB is recorded, which is still slightly lower than in case of Ch. 0.

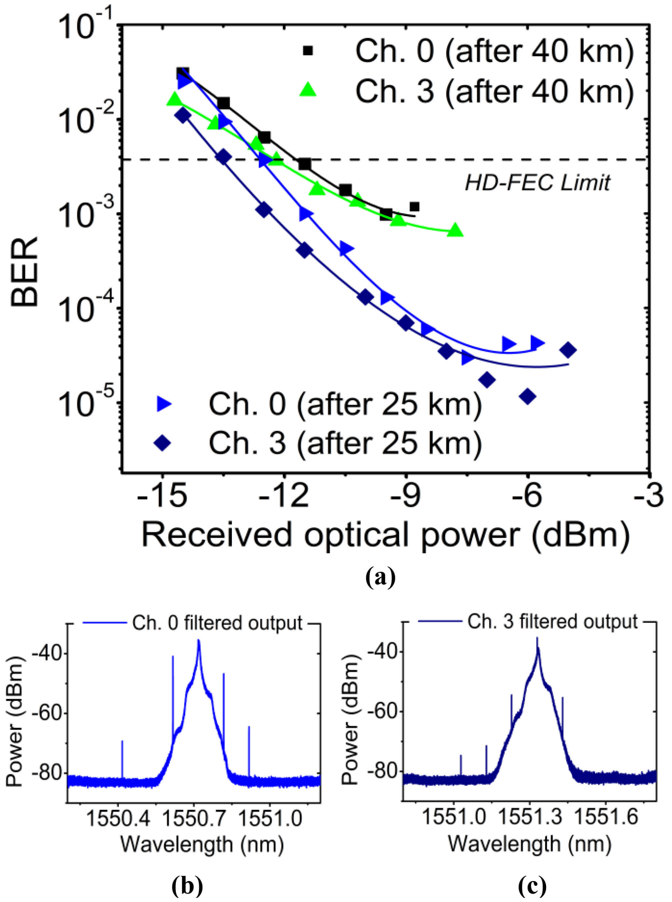


Fig. 6. (a) BER vs received optical power for two different scenarios in 4-QAM DMT system after 25 km and 40 km fiber transmissions. Filtered output spectra: (b) Ch. 0 and (c) Ch. 3.

Next, we compare the BER performance of two directly modulated channels (Ch. 0 and Ch. 3) and analyze the power penalty over different transmission lengths. Fig. 6(a) shows the BER plots of the two different comb tones (Ch. 0 and Ch. 3), modulated with data and transmitted over 25 km and 40 km of fiber. Figs 6(b) and (c), show the filtered output spectra of Ch. 0 and Ch. 3, respectively.

An important observation to be made is that Ch. 3, despite the low power of its injected comb tone, performs better than Ch. 0. This can be attributed to the reduced interference from the modulated unsuppressed comb tones. Since Ch. 3 corresponds to a comb tone with lower power than Ch. 0, all its adjacent comb tones also have less power than those next to Ch. 0 (seen in Fig. 6(b) and (c)). Hence, when the weaker unsuppressed comb tones adjacent to Ch. 3 are detected, they result in lower in-band interference than in the case of Ch. 0. Thus, lower power of the unsuppressed tones results in lower interference and lower power penalty.

B. 16-QAM DMT System

Fig. 7(a) shows the comparison plot of the BER versus ROP for the BtB and 25 km fiber transmission of Ch. 0 and Ch. 3, when both are modulated with a 16-QAM DMT signal. We observe a BER below the HD-FEC limit of 3.8×10-3 for both the cases. At the FEC limit, a power penalty of 2 dB is observed for Ch. 0 compared to Ch. 3. As discussed earlier, this penalty is due to the higher power of the unsuppressed comb tones, when demultiplexing the Ch. 0, as shown in Figs 6(b) and (c). Figs. 7(b) and (c) show the constellation diagrams of 16-QAM DMT signals for the Ch. 0 and Ch. 3 respectively, at an ROP of -6 dBm. From the constellation diagrams, we also observe more spread in the symbols, when Ch. 0 is modulated with data, compared to Ch. 3.

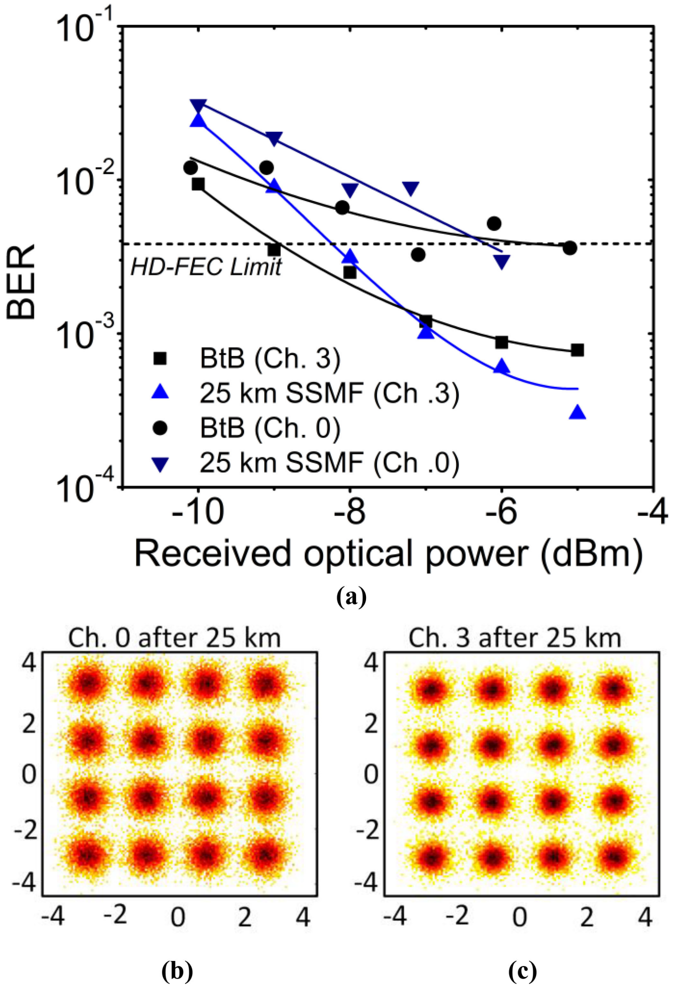


Fig. 7. (a) BER vs received optical power for BtB and 25 km fiber transmission of Ch.0 and Ch. 3 (low power channel $<$ 20 dB) modulated with 16-QAM DMT signals. 16-QAM DMT constellation diagramsat an ROP of -6 dBm and after 25 km SSMF transmission with (b) Ch. 0 and (c) Ch. 3 (low power comb line).

IV. COMPARISON OF PROPOSED SCHEME WITH CURRENT DCI TECHNOLOGIES

The DC transceiver market is quite fragmented, with specific transmitter models aimed particular data rates and transmission distances. Table I shows the comparison of key performance indicators (KPIs) associated with some currently used technologies in datacenters together with the proposed scheme [3], [4], [9], [21].

TABLE I
COMPARISON OF KPI'S ASSOCIATED WITH SOME CURRENTLY USED TECHNOLOGIES AND OUR PROPOSED SCHEME

Parameter	***100G-LR4***	***100G-ER4***	***400G-LR4/8***	***OFC + active demultiplexer***
Lane count	4	4	4/8	8[1]
Signal rate/lane	25.78 GBd	25 GBd	106/53 GBd	12.5 / 25 GBd[2]
Center wavelength	1310 nm	1310 nm	1550 nm	1550 nm[3]
Modulation format	OOK / NRZ	PAM4	PAM4	4/16-QAM DMT
Laser source	4 DMLs	4 EMLs	4/8 DFBs	OFC+DFB/lane[4]
TEC	250mW / lane	300 mW / lane	Required	Not a strict req. OFC provides fixed channel spacing[5]
Reach	10 km	40 km	40 km	40 / 25 km (DWDM)
Optical amplifier	Yes	Yes	Yes	No
Receiver	PIN	(SOA + PIN)	APD	PIN
Receiver sensitivity	-8.6 dBm	-21.6 dBm	< -9.1 dBm	-9.2 dBm[6]
Power budget	8.5 dB	18 dB	10.8 dB	17 /14 dB[6]
Cost	Low	Medium	High	Medium[7]

[1] Can be further increased through optimization of the FSR and channel bandwidth.
[2] Can be increased by increasing the signal bandwidth.
[3] Can also be realized in 1310 nm to extend the reach.
[4] Enables dense channel spacing.
[5] When integrated, temperature variation affects OFC and demultiplexer in a similar way.
[6] Proof-of-concept result, can be improved significantly.
[7] Integration and commercial production will reduce the cost.

V. CONCLUSION

In this paper, we experimentally demonstrate an OFC based transmitter comprising an active demultiplexer directly modulated with 4- and 16-QAM DMT signals. Through injection locking of a semiconductor laser with the desired OFC tone, the active demultiplexer not only acts as a filter, but also as an optical amplifier (operating in a constant power mode) and a data modulator of the filtered tone. Thus, the entire transmitter can be integrated onto a single chip, offering a significant reduction in the transmitter footprint, cost and energy consumption. Furthermore, the demultiplexer provides an enhanced channel count, as any comb tone with sufficient power to achieve a stable locking of the demultiplexer, can be used for the data modulation. Using the proposed transmitter configuration, we experimentally demonstrated the successful transmission of 12.5 Gb/s/λ 4-QAM and 25 Gb/s/λ 16-QAM DMT signals over 40 km and 25 km, respectively. Furthermore, the results prove that the proposed method has the potential to achieve an aggregate data rate of 100 Gb/s (8 × 12.5 Gb/s) for 4-QAM DMT and 200 Gb/s (8 × 25 Gb/s) for 16-QAM DMT over 40 km and 25 km of fiber transmission respectively. As such, the proposed method could be employed for DCIs and short reach applications. The SE of the system can be significantly improved, by optimizing the FSR of the OFC and the bandwidth of the data, in order to utilize all neighboring WDM channels for data modulation.

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