Performance evaluation of a comb-based transmission system employing multi-functional active demultiplexers

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Abstract: A compact OFC-based transmitter for short-reach applications is demonstrated. A single device is employed to implement OFC demultiplexing, amplification and direct modulation. Using this method, error-free data transmission over 3 km of fiber is achieved.
OCIS Code: 140.3520 Lasers, injection-locked; 130.7408 Wavelength filtering devices;

1. Introduction

Over the last decade, data traffic has increased in an unprecedented manner, mainly fuelled by the extensive usage of various bandwidth intensive applications. To address these demands, the utilization of the legacy fibre infrastructure in an optimum manner is important. Hence, optical networks are evolving towards flexible superchannel systems, employing spectrally efficient multicarrier transmission techniques, such as Nyquist WDM and CO-OFDM [1]. In such networks, the channel spacing of 12.5 GHz or even smaller could be used for optimum spectral utilization [2]. These closely spaced carriers introduce stringent requirements on the frequency stability of the transmitter, in order to avoid cross-channel interference. Precise wavelength control of an array of independent lasers is very difficult to achieve. An optical frequency comb (OFC) on the other hand, with its fixed free spectral range (FSR), is an ideal candidate to be used as a transmitter in such ultra-dense WDM systems. An added benefit of this precise FSR is the alleviation of the need for large guard bands between channels, enabling enhanced spectral efficiency of the system. While the benefits of using OFCs in ultra-dense WDM networks are evident, demultiplexing of such closely spaced carriers prior to modulation, remains a challenge. Conventional demultiplexing solutions, such as arrayed waveguide gratings and wavelength selective switches, do not possess sufficient bandwidth resolution to separate comb lines with FSRs < 12.5 GHz [3]. Moreover, these devices typically exhibit a high insertion loss, which together with the loss of the external modulators used for data modulation, lead to the need for optical amplifiers. This in turn results in an increased complexity and cost, as well as a degraded optical signal to noise ratio (OSNR). A generic architecture of a comb-based WDM transmitter, employing a conventional demultiplexing solution, is shown in Fig.1 (a).

An attractive alternative is to employ a laser-based demultiplexer based on optical injection locking. In such a device, the selection of a comb tone is achieved by injecting the OFC into a laser (demultiplexer) and aligning the wavelength of this laser with the desired comb line. As a result, the demultiplexer is injection locked by the selected tone i.e. it inherits its phase noise and follows its frequency drift [4]. Recently, we reported on the performance of an injection-locked based demultiplexer, in terms of the comb line suppression ratio (CLSR) and injection locking range (Δf), as a function of injected comb line power (CLP) [5]. In this work, we present the results of a proof-of-concept validation of a complete OFC-based transmitter, employing a multi-functional demultiplexer. The simultaneous demultiplexing, amplification and modulation of a comb line is realized using a single injection-locked demultiplexer. Error-free operation of a directly modulated 10.7 Gb/s data signal transmitted over 3 km of fiber is achieved. Such a multifunctional device can be employed as a compact and cost-effective transmitter for short reach applications.

2. Experimental setup

The proposed comb-based transmitter architecture is shown in Fig. 1(b). It comprises an OFC (FSR of 12.5 GHz), followed by a two-channel demultiplexing stage. The OFC is based on an externally injected gain switched laser (EI-GSL) [6]. The generated comb is split using a 50:50 coupler and injected into two commercially available distributed feedback (DFB) lasers (two active demultiplexers). Both DFBs exhibit a threshold current (I_{th}) of 12.5 mA and a modulation bandwidth of 14 GHz. When biased at $4\times I_{th}$, the average optical power emitted is 8.5 dBm (Demux 1) and 9 dBm (Demux 2). The wavelength of each demultiplexer is then temperature tuned to match that of the chosen comb line. The injected comb line power and the polarisation are optimised by inline variable optical attenuators (VOAs) and polarisation controllers. The CLP is a crucial parameter as it affects both the locking range (higher power leads to a larger locking range) and the CLSR (an increase in CLP reduces the CLSR) [5]. Thus, the injected power level is a compromise between a stable injection locking of the demultiplexer and the highest CLSR. In this paper, the CLP was adjusted to -31 dBm, which resulted in a CLSR of 37 dB (see Fig. 2(b)).

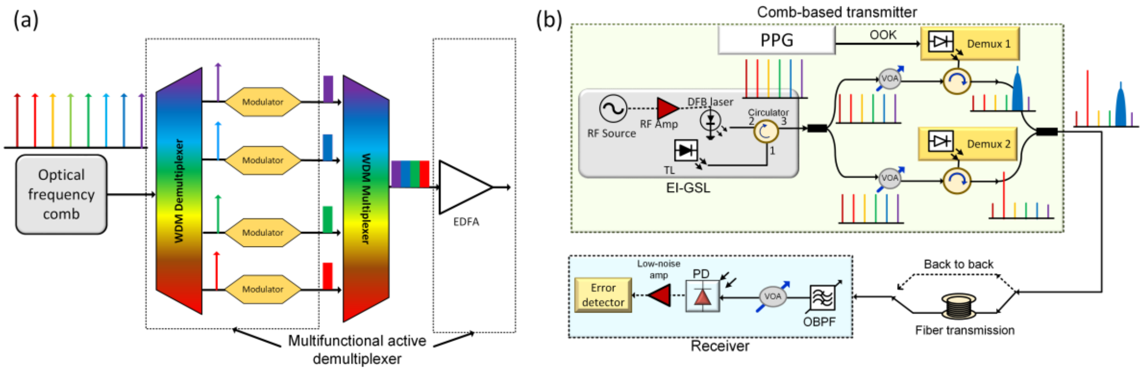

Figure 1: (a) Generic architecture of comb-based WDM transmiter system (dotted boxes show the functions realised by the active demultiplexer). (b) Experimental setup of the proposed comb-based transmission system. Here, VOA: variable optical attenuator, PPG: pulse pattern generator, PD: photodetector, OBPF: optical band pass filter, ED: error detector.

As the demultiplexer is a standard semiconductor laser, it can be directly modulated with data, thus removing the need for an external modulator as in Fig.1 (a). To demonstrate the modulator functionality, the demultiplexer is directly modulated with a 10.7 Gb/s data signal (2^{15}-1 PRBS, $2V_{p\text{-}p}$). Due to equipment constraints, direct modulation is applied to only one of the demultiplexers (Demux 1), before multiplexing the two channels using another 50:50 coupler. As it is a proof-of-concept experiment, a basic modulation format such as OOK is used. The combined channels are then transmitted over a 3 km of standard single mode fibre (SSMF). At the receiver, the modulated signal is filtered using an optical band pass filter and detected using a 20 GHz photodetector. The electrical signal is then amplified, by a low-noise amplifier, and the bit error ratio (BER) is measured using an error detector. The eye diagrams are recorded using a 50 GHz sampling oscilloscope.

3. Results and discussion

The optical spectra of the EI-GSL OFC is shown in Fig. 2(a). It consists of 11 lines (within 3 dB from the spectral peak), with an FSR of 12.5 GHz and an optical carrier to noise ratio of 50 dB (measured over a bandwidth resolution of 0.1 nm). The combined optical spectrum of the two demultiplexed comb lines, separated by 37.5 GHz, is shown in Fig. 2(b). It can be seen that for a CLP of -31 dBm, a CLSR of 37 dB is achieved. It is important to note that as the output power of the demultiplexer is much higher than that of the injected tone, the demultiplexer de facto amplifies the filtered comb line. In contrast to using an optical amplifier, this is achieved without addition of amplified spontaneous emission (ASE) noise. In this case, for a comb line power of -31 dBm, the power of the demultiplexed lines is 8.5 dBm and 9 dBm, demonstrating the ability of the demultiplexer to provide a gain of ~40 dB. The optical spectrum of the combined output of the demultiplexers, where Demux 1 is modulated with the data, is depicted in Fig. 2(c).

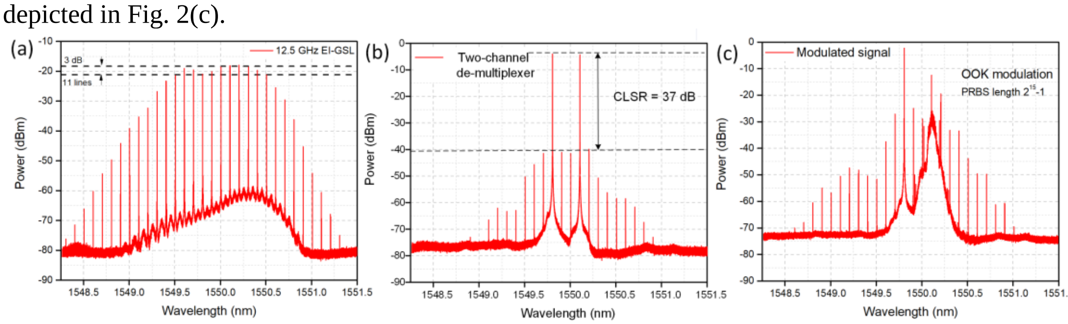

Figure 2: Optical spectra of (a) EI-GSL with FSR of 12.5 GHz, (b) combined demultiplexers output without data modulation and (c) combined demultiplexers output with modulated Demux 1. OSA resolution: 20 MHz, spectra (b) & (c) recorded with 5 dB attenuation before the OSA

The system performance is then evaluated, for three different scenarios, by measuring the BER vs. received optical power for a back-to-back (B2B) case and after 3 km fiber transmission. The three different schemes comprise a directly modulated Demux: (1) with no injection, (2) externally injected with a tunable laser (TL) and (3) externally injected with an OFC. The first scenario serves as a benchmark, while the second provides an insight into the impact of external injection on the performance of a directly modulated laser. Finally, the third configuration allows us to quantify the effect of the spurious comb tones on the performance of the OFC-based transmitter. For configuration 2 and 3, the injected power of the TL and the CLP were both set to -31 dBm.

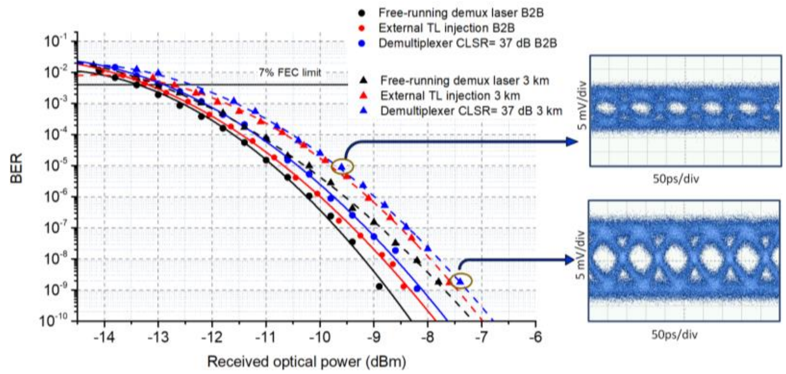

Figure 3: BER vs. received optical power: solid and dotted lines correspond to B2B and 3 km fiber transmission respectively. Insets are eye diagrams recorded at the indicated BERs.

The BER versus received optical power for all three cases is plotted in Fig. 3. The insets show the received eye diagrams of the OFC-based transmitter at BER of 1e-5 and 1e-9. From the BER plots, it can be seen that the stand-alone demultiplexer (configuration (1)) performs best in the B2B case, having a receiver sensitivity of -8.8 dBm. Nevertheless, it suffers from the highest penalty of 1.2 dB (at a BER of 1e-9), when transmitted over the 3 km of SSMF. The direct modulation results in a large frequency chirp, which exacerbates the effect of chromatic dispersion, leading to such a large penalty. In the B2B cases for configurations (2) and (3), there is a 0.5 and 0.7 dB penalty respectively, incurred at a BER of 1e-9 with respect to the reference (configuration (1)). This is a consequence of a reduction in the extinction ratio caused by the external injection [7]. However, the additional penalty due to the fibre transmission is smaller for both these cases, than for the free running laser. The transmission penalty for configuration (2) and (3) are 0.9 dB and 0.8 dB respectively (compared to their respective B2B cases). This improved resilience to the transmission impairments can be credited to the reduction in chirp due to external injection [7]. It is also important to note, that there is no additional penalty due to the presence of the spurious comb tones in configuration (3). It is expected that for longer transmission distances, the impact of the limited CLSR will become more pronounced. This is due to all the spectral components, passing through the demultiplexer, being modulated with the same data. As they traverse sufficiently long transmission distances, chromatic dispersion will introduce a phase mismatch between the different signals, causing them to interfere at the receiver. 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 achievable chirp reduction due to the external injection.

4. Conclusion

We have demonstrated an OFC-based transmitter employing an active demultiplexer. The latter is a single device able to simultaneously perform demultiplexing, ultra-low noise optical amplification and data modulation. The potential of the proposed method has been verified by successfully demultiplexing a 12.5 GHz spaced comb line, modulating it with 10.7 Gb/s data and achieving error free operation when transmitted over 3 km of SSMF. The results also show that in such a scenario, the chirp-induced penalties, due to direct modulation, can be reduced. As the proposed architecture is entirely based on direct modulation (for both comb generation and data modulation) it is simple and cost efficient. Furthermore, it can be integrated onto a single chip and does not require additional amplification stages, thus offering a significant reduction in the transmitter footprint and energy consumption. With such excellent features, the proposed technique is well suited for next generation intra data centre networks. We aim to investigate the use of advanced modulation formats such as PAM4 and OFDM in the near future.

Acknowledgment: This work was supported by the Science Foundation Ireland (SFI) 15/CDA/3640, SFI Industry Fellowship (17/IFB/5385) and the SFI/European Regional Development Fund (13/RC/2077).

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