Demonstration of CoWDM Using a DPSK Modulator Array with Injection-locked Lasers

S.K. Ibrahim, A.D. Ellis, F.C.G. Gunning, and F.H. Peters

Abstract: In this paper a practical implementation of CoWDM is demonstrated for the first time using injection locked lasers and a DPSK modulator array. For a 31.99Gbit/s system (3 sub-carriers at 10.664Gbit/s) the null-to-null spectral bandwidth was only 42.656GHz and the average receiver sensitivity measured was -33.5dBm when all sub-carrier phases were optimized.

Introduction: The rapid growth in video based Internet applications is increasing the demand for higher speed optical transmission systems for the access, metro-core, and long haul networks. This will result in the need for bandwidth efficient telecommunications systems. One promising approach is to use multi-carrier spectrally efficient transmission techniques [1-5] with the sub-channel spacing equal to the symbol rate of each sub-channel. This can be achieved by either optically generated coherent wavelength division multiplexing (CoWDM) [1,2], or electronically [3-4] or optically [5] generated orthogonal frequency division multiplexing (OFDM). These techniques offer the prospect of high aggregate capacity [2] and spectral efficiency [3], with impairment tolerance scaled with the symbol rate of each sub-carrier. To date however, the power efficiency of the transmitters employed has been low, either due to excess losses associated with comb generation, or due to the implications of the non-linear modulator transfer function and peak to average power ratio for OFDM systems.

In this paper, we demonstrate for the first time the use of injection locked lasers as the comb source for CoWDM, offering the prospect of enhancing the power efficiency and we investigate the impact of modulating both nearest neighbour sub-channels with independent patterns using a differential phase shift keying (DPSK) modulator array, resulting in an optically generated multi-carrier 31.99Gbit/s (3 sub-carriers at 10.664Gbit/s) CoWDM system which retains the required optical signal-to-noise ratio (OSNR) improvements of DPSK.

CoWDM System using Modulator Array: A general schematic of a CoWDM system using a modulator array with injection locked lasers is shown in Fig. 1. The CoWDM laser source is used to generate the equally spaced sub-carriers at a frequency spacing equal to the symbol rate of a single channel. To date the sub-carriers have been generated using a modulator-based comb generator [1, 2, 5] operated to obtain equal power per comb line, rather than for maximum output power. The sub-carriers are then de-multiplexed in order to separate each sub-carrier before modulation with the corresponding data signals. At high sub-channel counts, to maintain an adequate OSNR, an optical amplifier is typically employed between the comb generator and the modulator array. An alternative method is to injection lock an array of CW or tunable lasers [6] enabling each laser to be phase locked to one of the selected comb lines as shown in Fig. 1 (left). The injection locked lasers readily enable equalisation of the sub-channel powers, relaxing power and flatness constraints imposed on the primary comb generating modulator. Since the required seed signal power for each injection locked laser is low [6] we also anticipate improved power efficiency from this scheme.

At the receiver side of a CoWDM system, stringent design specifications for the de-multiplexing filters are required for crosstalk-free operation. For a simpler de-multiplexer, comprising of a half bit delay asymmetric Mach-Zehnder interferometer (AMZI) followed by two arrayed waveguide gratings (AWG) [1,2] as shown in Fig. 1 (right), residual inter-sub-channel crosstalk still exists, the impact of which depends on the phases of the sub-carriers (ϕ_k). Controlling the phase of each sub-channel at the transmitter such that each is incremented by $\pi/2$ with respect to its neighbour enables the elimination of signal-crosstalk beating at the decision point. Direct or coherent detection can be used to receive intensity or/and phase modulated data signals on the CoWDM sub-channels. In this paper we also demonstrate, for the first time, more than two sub-channels modulated independently, unlike previous demonstrations of optically generated OFDM/CoWDM which have employed only two modulators, either for a two sub-channel system [5] or for modulation of odd and even sub-channels [2]. Consequently, penalties which may arise from differences in the patterns of the two nearest neighbours are considered here for the first time.

Experimental Setup: The experimental configuration is shown in Fig. 2, where the transmitter emulates Fig. 1 (left). The output of a fibre laser based seed source (1553.175nm) was split as follows; 10% was used as the centre sub-carrier (bypassing the injection locked laser for simplicity), and the remaining 90% was used to generate a 3-line comb signal spaced at 10.664GHz using a single Mach-Zehnder modulator (MZM). The comb signal then passed through a polarization maintaining (PM) circulator and splitter to injection lock two DFB lasers, corresponding to the left and right spectral lines from the centre sub-carrier, resulting in the left and right sub-carriers spaced 21.328GHz apart. Due to the low power of the 3-line comb, a moderate injection locking bandwidth was achieved such that the desired comb line could be selected by a given injection locked laser by current tuning alone with no additional optical filters. The 21.328GHz beat signal between the left and right sub-carrier was observed at the other output of the circulator as shown in Fig. 2 (left), confirming that both lasers were successfully injection locked in frequency and phase.

Each of the 3 sub-carriers were modulated by a 10.664Gbit/s electrical data stream with a pseudo random bit sequence (PRBS) length of 2^{31}-1 with 3 separate PM fibre pigtailed DPSK modulators (A, B, and C corresponding to the right, centre, and left sub-channels, respectively). A 10-bit and 7-bit delay was achieved between the data streams A-B, and B-C, respectively using electrical delay lines for de-correlation. A piezo-electric fibre stretcher was inserted after the output of each injection locked DFB laser in order to adjust the left and right sub-carrier phases to be orthogonal with respect to the centre sub-carrier, minimizing the residual crosstalk. The 3 DPSK modulated sub-carriers were then combined in a PM fibre pigtailed planar waveguide power combiner resulting in a 31.99 Gbit/s DPSK CoWDM signal with a null-to-null spectral bandwidth of 42.656GHz as shown in Fig. 2 (right).

At the receiver side a variable optical attenuator (VOA) was used to vary the input power to an Erbium doped fibre amplifier (EDFA) pre-amplifier to measure the receiver sensitivity. The pre-amplifier was followed by an optical 0.3nm-bandwidth tunable band pass filter (BPF). An AMZI (Kylia) with a free spectral range (FSR) of 21.33GHz was used as a dis-interleaver to separate the odd and even sub-channels, and each of which were, in turn, launched to the second EDFA. The signal then passed through a bandwidth adjustable filter, which was optimized for each received sub-channel (a bandwidth of 50GHz for the centre channel and 30GHz for the outer channels). Finally a 10.664Gbit/s DPSK demodulator (1-bit delay AMZI) was used to demodulate the DPSK signals. The demodulated signal was detected using a balanced photodiode and amplified using a limiting differential amplifier before being fed to an error detector (ED) and a high speed oscilloscope (Osc). The demodulated eye diagram for the right (A), centre (B), and left (C) sub-channels of the received 31.99Gbit/s DPSK CoWDM signal measured when the amplifier was operated in the linear regime are shown in Fig. 3, where the eye is open in the middle and the residual cross talk is apparent at the bit transitions. The performance of the system was also evaluated by measuring the bit error rate (BER) curves of the 3 received CoWDM sub-channels as shown in Fig. 4 for the cases when the phase of the sub-carriers were optimized to get the lowest BER and when the phases were detuned resulting in a degraded BER. The receiver sensitivity at a BER of 10^{-9} for the CoWDM sub-channels DPSK A, B, and C were measured to be -33.88, -32.75, and -33.86dBm respectively when the phase of the sub-carriers were optimized. Compared to the back-to-back (B2B) single sub-carrier receiver sensitivity of -39.8dBm (measured using centre sub-channel B with same filter configuration), the outer sub-channels (A, C) and the centre sub-channel (B) had a net penalty of 1.1dB, and 2.3dB, respectively, when the expected 4.7dB shift is taken into account. The additional 1.2dB penalty for the centre sub-channel is attributed to the additional contributions from the two neighbouring sub-channels, which in this experiment carry different patterns, but would be eliminated with an ideal matched filter used at the receiver. With the sub-carrier phases adjusted away from their optimum positions, the performance of the centre channel, with two interfering neighbours, was significantly degraded whilst modest penalties were observed for the outer channels as shown in Fig. 4.

Conclusions: We have demonstrated for the first time the compatibility of CoWDM systems with phase modulated signals in a practical configuration using injection locked lasers and a modulator array operating at a symbol rate of 10Gbaud. By extending the number of sub-carriers, this scheme is a potential candidate for practical high speed multi-carrier transmission systems.

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Figure captions:

Fig. 1 Schematic representation of a CoWDM system using a comb generator and array of injection locked lasers and modulators

Fig. 2 Experimental 31.99Gbit/s DPSK CoWDM system

Fig. 3 Eye diagrams of the 3 demodulated CoWDM DPSK sub-channels DPSK A, B, and C

Fig. 4 BER vs. total received power for 31.99Gbit/s DPSK CoWDM.

Figure 1

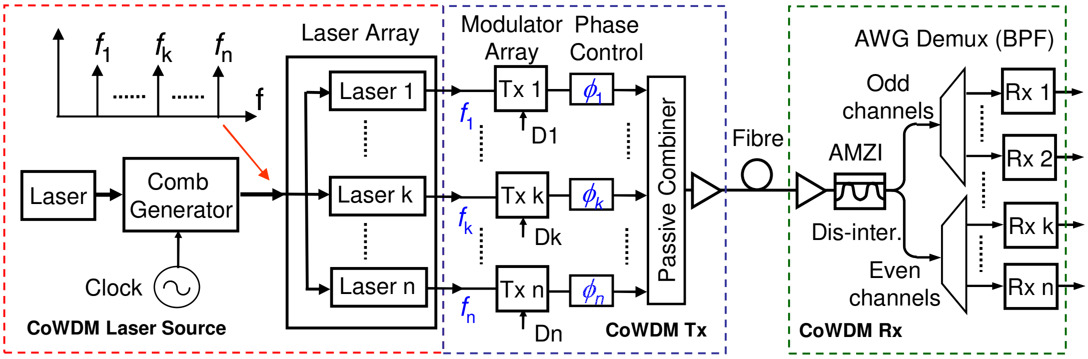

Figure 2

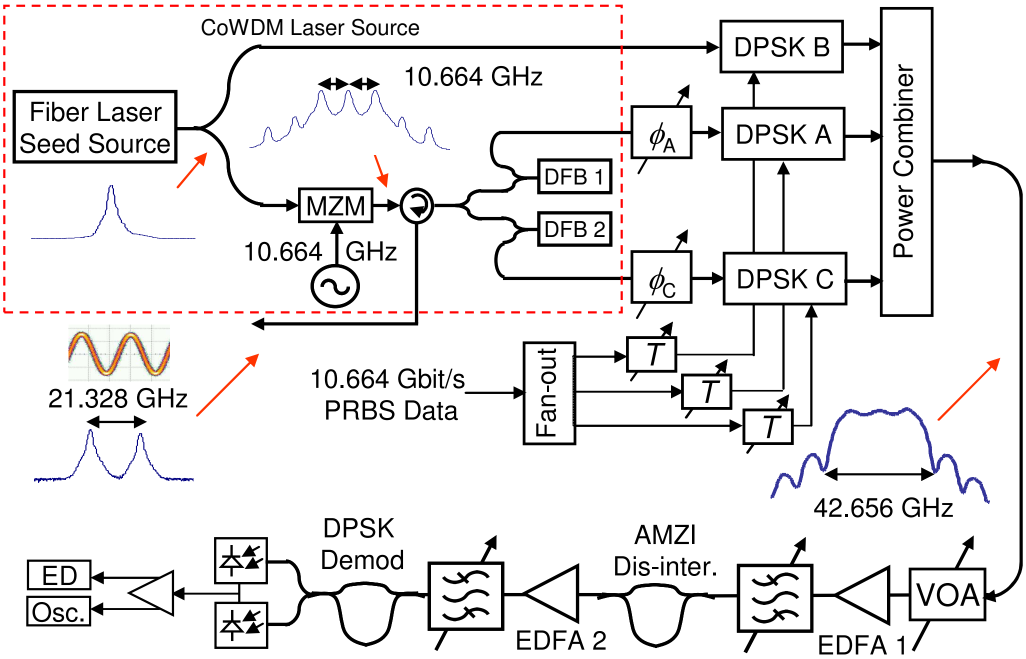

Figure 3

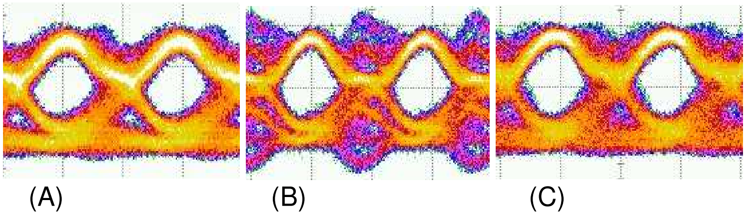

Figure 4