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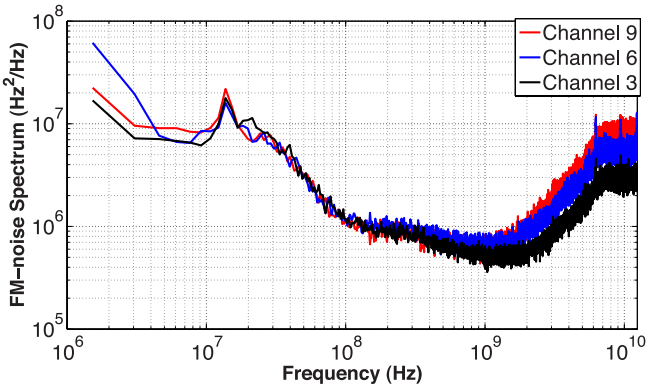

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200-Gb/s Baudrate-Pilot-Aided QPSK/Direct Detection With Single-Section Quantum-Well Mode-Locked Laser

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Abstract: We demonstrate transmission of a 200-Gb/s superchannel over 3-km single-mode optical fiber (SMF) targeting intra-data center interconnect applications using a novel single-section quantum-well passive-mode-locked laser that generates an optical frequency comb. The transmitted optical signal consists of 16 subcarriers filtered from the optical frequency comb of the laser and modulated with an advanced modulation format of Baudrate-pilot-aided quadrature phase-shift keying (QPSK) modulation that enables direct detection. Bit error rates below the forward error correction limit have been confirmed for all subcarriers, and the detailed noise characteristics of the passive-mode-locked laser have been investigated to support the understanding of the system performance.

Index Terms: Mode-locked laser, optical interconnects, advanced modulation formats.

1. Introduction

Optical communications employing advanced modulation formats, which offer high spectral efficiency, is a key technology to address the capacity increment in wavelength division multiplexing (WDM) optical networks and is now being widely deployed in commercial systems [1]. Short-reach optical interconnects in datacenter and metro/access networks pose a more stringent requirement on cost and energy consumption while still needing to keep pace with the exponential growth in traffic [2]. However, the need of tens of wavelength-stabilized distributed feedback lasers from discrete components to produce optical carriers for WDM constitutes a severe limitation for a widespread deployment of this technology within short reach interconnects. Even though large scale III–V photonic integration [3] shows the ability to significantly reduce the complexity of the transmitter, the cost, yield, energy consumption as well as the stability is still a real challenge for commercial applications.

A promising solution to this problem consists in replacing a multitude of independent oscillators with a single optical frequency comb (OFC) generator, providing several equally spaced wavelength channels [4]–[7]. Super-channel transmission employing OFCs with coherent detection and high order modulation formats, such as quadrature phase-shift keying (QPSK) or 16-quadrature amplitude modulation (16-QAM), can be used to demonstrate Terabit/s class data transmissions over a single mode fiber [8]. However, these techniques might be too complex to be practically implemented in cost and energy sensitive systems, such as data centers or high-performance computers where a very large number of short-reach optical links are employed. In contrast, an intensity modulation/direct detection technique with its simplicity would be a cost effective approach for this scenario [9]. Recently we presented a novel modulation scheme, named Baudrate-Pilot-Aided QAM (BPA-QAM) [10], which has the ability to improve spectral efficiency by migrating to higher order QAM while still taking advantages of direct detection techniques. The basic concept of BPA-QAM involves transmitting a pilot tone that is coherent with the optical carrier in order to provide a phase reference at the receiver. Direct detection of the optically coherent data signal and pilot tone then cancels the phase/frequency noise of the laser source. For spectral efficiency, the pilot tone frequency is set to coincide with the baudrate, thus eliminating the guard band by placing the tone at the edge of the main lobe of the symbol spectrum.

In this work we demonstrate for the first time, the application of this BPA-QPSK modulation scheme in a WDM system using a single-section quantum well passive MLL [11] as the OFC. These passive MLLs are ideal candidates for data center interconnects based on the emerging silicon photonics platform as they can be connected to Si chips using, for example, photonic wire bonding technology, while their longitudinal modes can be individually de-multiplexed and modulated, respectively, by means of Si-based ring resonator filters and modulators. In this work a 16 channel MLL has been used to transmit a line rate of 200 Gb/s over 3 km SMF fiber with the 16-subcarriers employing BPA-QPSK modulation/direct detection at 6.25 Gbaud without any dispersion compensation. In addition, the noise characteristics of the OFC from MLL have been investigated to gain an understanding of the system performance. The paper demonstrates a cost effective and compact solution with single-section quantum well MLLs and advanced modulation scheme to address the requirements in the short reach optical interconnects.

2. Noise Characteristics of the Mode-Locked Laser

The device employed in this work is a 1-mm-long, single-section 2-μm-width ridge waveguide passive-mode-locked laser with as-cleaved facets. The component is fabricated from an epitaxial structure grown by gas source molecular beam epitaxy on an InP substrate and consists of a single InGaAsP strained quantum well embedded in 214-nm-thick InGaAsP barriers. This design provides a low optical confinement factor of about 1%, resulting in a reduced impact of spontaneous emission on the amplitude and phase noise of laser longitudinal modes [11], [12]. The laser under test was mounted on a copper base and operated at temperature 20 °C using a Peltier cooler and a temperature controller with a stability of ±0.1 °C. The laser, emitting around 1.56 μm, features a threshold current of 16 mA and output power at saturation of 20 mW. For injection currents above 50 mA, a relatively flat comb spectrum with FWHM on the order of 4 to 6 nm is observed. In the experiment, the device is operated at a bias current of 155 mA, which provides an average power in the fiber of 10 dBm. Further description of the device operation could be found in reference [13]. In this work, we mainly investigate in details the noise characteristics of the proposed mode-locked laser and its transmission system performance. The output light from the laser is coupled to single-mode fiber for the experiments by tapered-lensed fiber. The output optical spectrum of the mode-locked laser is shown in Fig. 1. This frequency comb source will be used for noise characterization and transmission system experiments later.

For detailed phase noise characterization of the laser comb lines, we utilized the coherent delayed self-homodyne method in [14]. The output OFC from the MLL laser passes through a

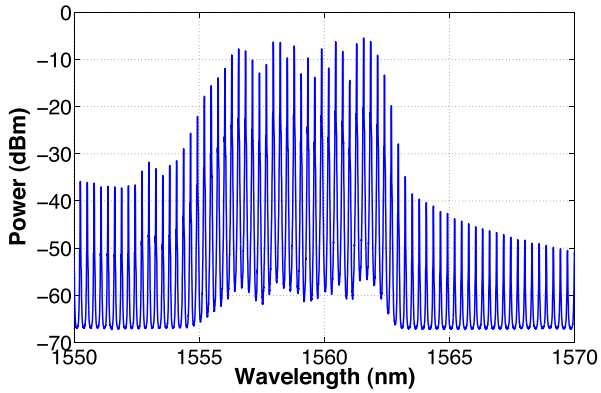

Fig. 1. Optical spectrum of output light from quantum-well mode-locked laser.

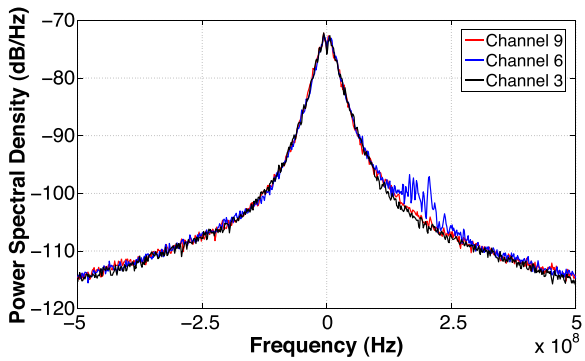

Fig. 2. E-field power spectral density from self-homodyne measurements of selected channels of quantum-well mode-locked laser.

narrow band optical filter to select the individual line from the comb source. An C-band optical amplifier is used to compensate for the loss (coupling loss and filter loss) and bring the optical power to sufficient SNR level for phase noise characterization. The signal is then splitted in a 50/50 coupler, one of the two arms was delay by the 25 km SMF fiber delay line and recombined in the optical 90° hybrid. The contribution of the ASE noise from the EDFA to the measurement results is negligible and has been carefully confirmed in the experiments. The phase noise measurement results of selected individual channels are shown in Fig. 2 for the E-field power spectral density and the FM-noise spectra in Fig. 3.

Even though the FM-noise spectrum of the individual channels in Fig. 3 shows a high level of low frequency noise which starts to increase at around 200 MHz, the intrinsic linewidth of each channel from the white FM-noise is around 1 MHz. This explains the observed delayed self-heterodyne optical linewidth of individual lines in the range of ~11 MHz as in Fig. 2. As illustrated in Fig. 3, the FM noise spectra of different channels demonstrate similar levels of phase noise. The MLL laser also has increased phase noise in the FM-noise region above 2 GHz, attributed to the relaxation oscillation phenomenon. These phase noise processes would severely impact the performance of these devices in optical coherent communications system employing advanced modulation formats [15].

In addition to the phase noise characterization, the relative intensity noise (RIN) of the mode-locked laser is also evaluated. The RIN measurement has been carried out for the entire optical frequency comb and for a particular channel within the comb. Similar to previous phase noise characterization, for characterizing RIN of individual channel, a narrow band optical filer has been used. Optical amplification is also provided to compensate for the loss. The RIN measurement results of the MLL laser are shown in Fig. 4. The RIN of an individual channel is quite

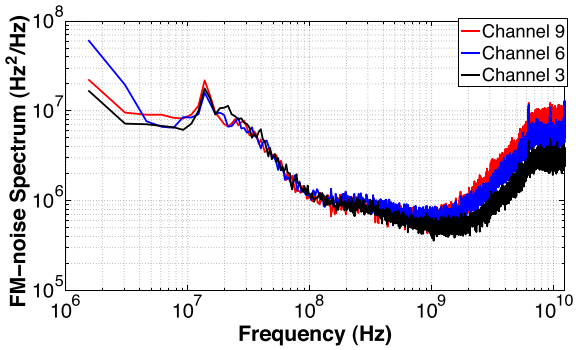

Fig. 3. FM-noise spectrum from self-homodyne measurements of the selected channel of quantum-well mode-locked laser.

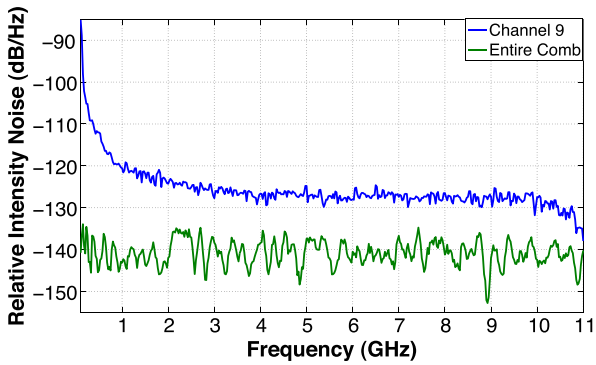

Fig. 4. RIN measurements for selected channel and entire OFC of quantum-well mode-locked laser.

large, above −130 dB/Hz, and about 10 dB higher than the RIN level of the entire comb due to mode partition noise. This level of RIN can also lead to degradation in system performance [10], as will be presented in the next section.

3. Baudrate-Pilot-Aided QPSK With Mode-Locked Laser

We subsequently carried out the super-channel BPA-QPSK transmission experiment employing the MLL as the optical frequency comb source. The system experiment setup is shown in Fig. 5. The output optical comb from the MLL laser as in Fig. 1 is firstly filtered to obtain 16 lines (spacing ~34 GHz), amplified and modulated by an IQ modulator. The filtered and amplified 16 subcarriers for transmission experiment are shown in Fig. 6. The 6.25 Gbaud BPA-QPSK signal [10] is generated offline and loaded to an arbitrary waveform generator (AWG). The output signal from the AWG is electrically amplified and modulates the 16 carriers, giving a total line rate of 200 Gbit/s. A wavelength selective switch is used to split the odd and even channels. The odd channels are then de-correlated by 5 m SMF fiber and combined in a 50/50 coupler. The multiplexed super-channel (16 subcarriers) is transmitted over 3 km SMF fiber for evaluation for short-reach optical interconnect applications in data centers.

The received optical signal is then amplified and filtered out by a narrow-band optical filter for individual channel measurements. A commercial 10 Gb/s PIN-photodiode with integrated TIA is used for direct detection of the 12.5 Gb/s BPA-QPSK signal. A Tektronix real-time scope is utilized as a high speed ADC to digitize (at 50Gsample/s sampling rate) the output electrical signal from the photo-receiver and store for off-line DSP processing. The performance for each channel has been examined, with more than 1.2 million bits received and used for estimating BER for each data point in the BER measurement. This allows for good accuracy when estimating BER down to 10^{-5}. The power budget of the system experiment could be summarized as

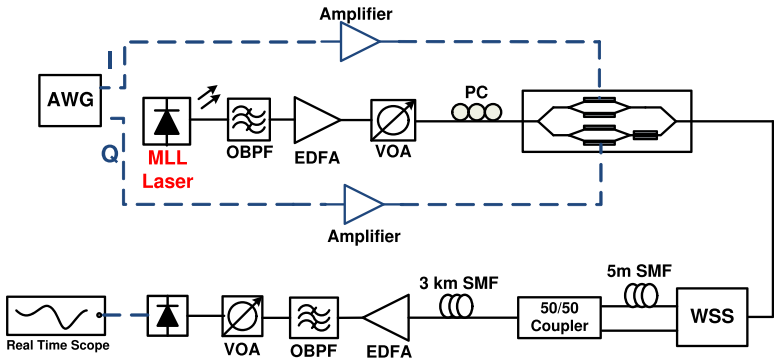

Fig. 5. Transmission experiment setup for baudrate-pilot-aided QPSK transmission employing quantum-well mode-locked laser.

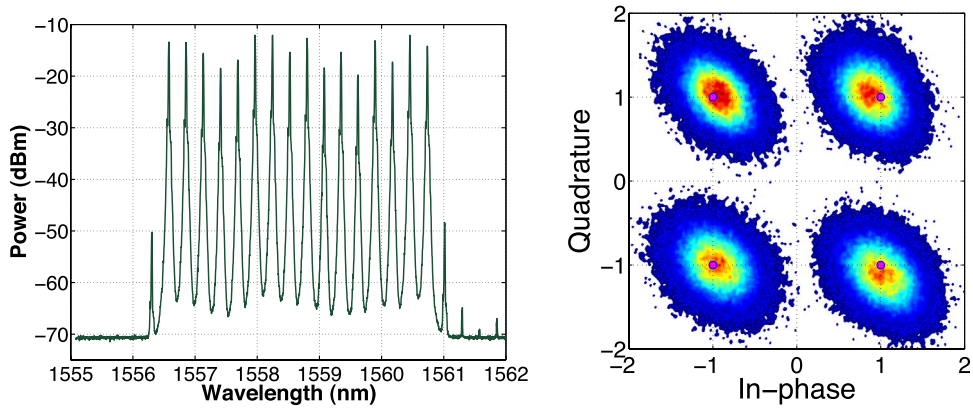

Fig. 6. (Left) Optical spectrum of 16 transmitted channels and (right) received constellation of channel 9 at −12 dBm of baudrate-pilot-aided QPSK.

follows. After the 16 channels from the MLL laser source are filtered and amplified, the total output power is +19 dBm; the loss from signal modulation and channel de-correlation is 25 dB which results in a total transmit power of −6 dBm, or −18 dBm per channel. Taking into account a 30 dB gain EDFA at the receiver, and a required receiver sensitivity of −13.5 dBm per channel, there is power margin of around 24.5 dB for optical fiber loss and insertion loss due to the filter at the receiver. Assuming the filter insertion loss is around 3.5 dB maximum that would leave 21 dB for system margin and fiber loss.

The BER performance versus received optical power of channel (subcarrier) 9 and 16 are shown in Fig. 7. An example of the received QPSK constellation at −12 dBm received power for channel 9 is illustrated in the inset of Fig. 6. The slightly elliptical shape of the constellation points is attributed to the nonlinearity of the electrical amplifier and the IQ modulator at the transmitter. The two channels show similar BER performance. For a reference, we employed a single mode external cavity laser (ECL) as the optical source for the transmission instead of the MLL laser. Compared to the baseline performance from the ECL laser, the BER performance of the individual subcarriers from the MLL laser experiences a 1.5 dB penalty at $\mathrm{BER} = 10^{-3}$. This penalty can be explained by the high level of RIN noise of each individual channel (above −130 dB/Hz) as characterized in the previous section.

The performance of all subcarriers in the super-channel is subsequently measured by maintaining the received power for each channel at −12 dBm and measuring the BER. Fig. 8 presents the BER performance of 16 individual subcarriers. All subcarriers demonstrate BER performance well below the FEC limit. Across 16 channels, the system experiences a fluctuation

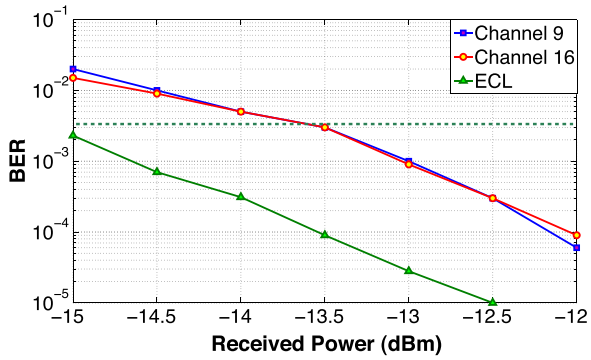

Fig. 7. BER measurement for channels 9 and 16 of BPA-QPSK employing quantum-well mode-locked laser.

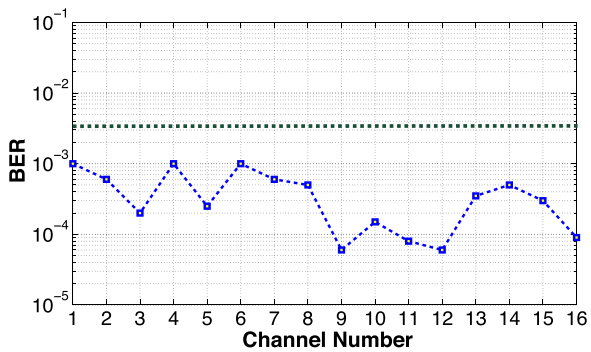

Fig. 8. BER of 16 channels at −12-dBm received power of BPA-QPSK employing the quantum-well mode-locked laser.

in performance mainly due to the variation in output power for each comb line as observed in Fig. 6. However, this drawback can be mitigated in a real gain-equalized transmission system.

4. Conclusion

In this paper, we have reported the proof-of-concept experimental demonstration for transmission of 200 Gb/s super-channel (186 Gb/s after FEC) using optical frequency comb source from a novel single-section quantum well passive-mode-locked laser with BPA-QPSK modulation scheme. All subcarriers demonstrated BER performance well below FEC limit. In addition, detailed noise characteristics of the optical frequency comb source from the MLL laser have been carried out to understand system performance. The total bitrate of the proposed system would be increased higher by migrating to higher order modulation format such as 16-QAM and employing faster electronics at transmit and receive side. As an example, deploying 16-QAM at 25 Gbaud on each sub-carrier, with a MLL with larger free spectral range than 34 GHz, a bitrate of 1.6 Tb/s could be achieved. The results suggest that BPA-QAM modulation scheme, in combination with OFC from a passively MML, is a cost effective solution that is suitable for short reach optical interconnect applications.

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