Multi-Channel Coherent Optical System Based on A High Power Fabry-Perot QW Laser Diode

Sharmila Raisa[1], Shalmoli Ghosh[1], Maurice O'Sullivan[2], Charles Laperle[2], Rongqing Hui[1]

1: Dept. of Electrical Engineering and Computer Science, University of Kansas, Lawrence, KS 66045 USA

2: Ciena Corporation, Ottawa, ON, K2K 0L1, Canada

Author email: rhui@ku.edu

Abstract: We demonstrate 20-channel coherent transmission using a high-power single-section QW FP-laser diode over 78.3 km single mode fiber. The system capability can reach > 4Tb/s with a single laser in the transmitter using polarizations multiplexing.

1. Introduction

Wavelength division multiplexing (WDM) is a key mechanism in modern fiber optic systems to meet the demand of rapid network traffic growth. Complex optical field modulation and coherent detection further increases the bandwidth efficiency and flexibility of optical transmission. In such systems, each WDM channel requires a narrow-linewidth and frequency-stabilized laser diode as the optical source, so that complexity and energy consumption stack up quickly as the channel number increases. Multi-wavelength laser sources have become attractive for WDM applications in which a single laser diode can provide tens of equally spaced spectral lines, known as *optical frequency combs* (OFC). Quantum-dot and quantum-dash based OFCs have been developed to provide mutually phase synchronized spectral lines with low relative intensity noise (RIN) of each spectral line thanks to their predominantly inhomogeneous broadening gain mechanism [1]. Quantum-well (QW) based OFCs have also been demonstrated to have higher power efficiency, and system application has been reported in which single-sideband (SSB) OFDM modulation and direct detection was used to avoid the use of low frequency region of up to 2 GHz where the RIN level is high [2]. For both quantum-dot/dash and QW based OFCs reported so far, although the differential phase noise between adjacent spectral lines can be quite low, the phase noise of each individual spectral line remains high with the linewidth in the tens of MHz level, which hampers their applications in systems with coherent detection. The output power levels of these lasers reported so far are between 1 mW and 20 mW, and the power of each spectral line is typically less than -5 dBm. The low power levels of these OFCs not only requires excessive optical amplification in an optical system which is associated with the generation of optical noise, it is also responsible for the relatively broad spectral linewidth of each spectral line, because the linewidth is inversely proportional to the optical power as indicated by the well-known Schawlow–Townes formula. In this work, we demonstrate coherent system application of a single section QW Fabry-Perot (FP) laser diode with >120 mW optical power at the fiber pigtail, and a mode spacing of 36.14 GHz. By employing 20 spectral lines in a system experiment each carrying 30 GBaud 16-QAM signal at single polarization over 78.3 km single mode fiber. Potentially the single laser in the transmitter (Tx) has the capability of supporting a 2.15 Tb/s (4.3 Tb/s for dual polarization) transmission capacity considering 11% FEC and maintenance overhead.

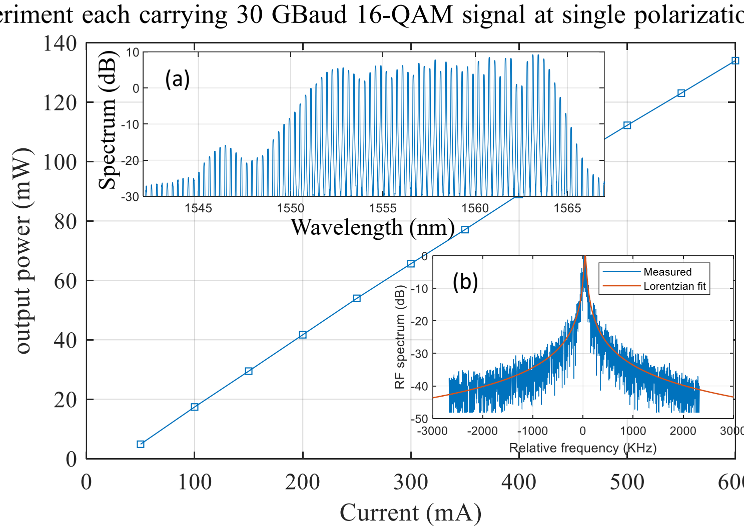

Fig. 1. Laser PI curve. Inset (a): optical spectrum at 600 mA current, and (b) mixing RF spectrum fitted with Lorentzian curve with 36.14 GHz center frequency and 20 kHz FWHM linewidth.

2. Device Characterization:

The device used for our study is a single-section InGaAsP QW FP laser emitting in the 1550 nm wavelength window with the structure similar to [3]. The laser output is coupled to a polarization-maintaining (PM) fiber after an optical isolator. In contrast to FP diode lasers made of bulk semiconductor materials with strong mode partition noise, FP laser diodes made of QW structures can have much lower mode competition, often explained as modelocking supported by spatial and spectral hole burning mechanisms [4]. The simplicity of FP structure also allows high power operation compared to distributed feedback (DFB) lasers. Fig.1 shows the measured current-power relation of the laser used in the experiment. At 600 mA injection current the total output power from the fiber pigtail is approximately 130 mW at 21°C temperature. The optical spectrum shown in inset (a) of Fig. 1 indicates that there are about 30 longitudinal modes spanning across a 10 nm bandwidth. Mode spacing of 36.14 GHz is primarily determined by the FP laser cavity length. The mixing between adjacent spectral lines is measured by an RF spectrum analyzer after a high-speed photodiode, and the mixing spectrum is shown in inset (b) of Fig. 1 which can be fitted by a Lorentzian line shape with a center frequency of 36.14 GHz and 20 kHz FWHM linewidth.

In addition to the optical power, RIN and phase noise of each spectral line are also important parameters for system applications. We use a wavelength-selective switch (WSS) to select individual spectral lines for measurements. Fig. 2 (a) shows the RIN spectra of 20 individual spectral lines across 5nm spectral window (1553.8 nm to 1559.4 nm). The RIN levels in the low frequency region of up to 200 MHz range from -110 dB/Hz to -98 dB/Hz, and they reduce rapidly at high frequencies. The normalized variance of power fluctuation, equivalent to the integrated RIN over the frequency, is shown in Fig. 2(b) (left y-axis), together with the average power of each spectral line (right y-axis), which indicate the non-uniformity of these spectral lines. Fig. 2(c) shows FM noise power spectral density (PSD), $S_{FM}(f)$, of the 20 spectral lines measured with coherent detection. For a laser with ideal Lorentzian line shape, S_{FM} is independent of frequency, and is related to the commonly used spectral linewidth by $\Delta v = \pi S_{FM}$. For high-speed coherent optical system applications, low frequency components of $S_{FM}(f)$ can be tracked by carrier phase recovery in the DSP, and system performance is most sensitive to high frequency components in the GHz region [5]. Fig. 2(c) indicates that the "Lorentzian equivalent" linewidth [5] in the 1 – 2 GHz region is less than 100 kHz, which generally meets the requirement of coherent systems. The major reason for the narrow spectral linewidth is attributed to the high optical power so that stimulated emission overwhelms the spontaneous emission.

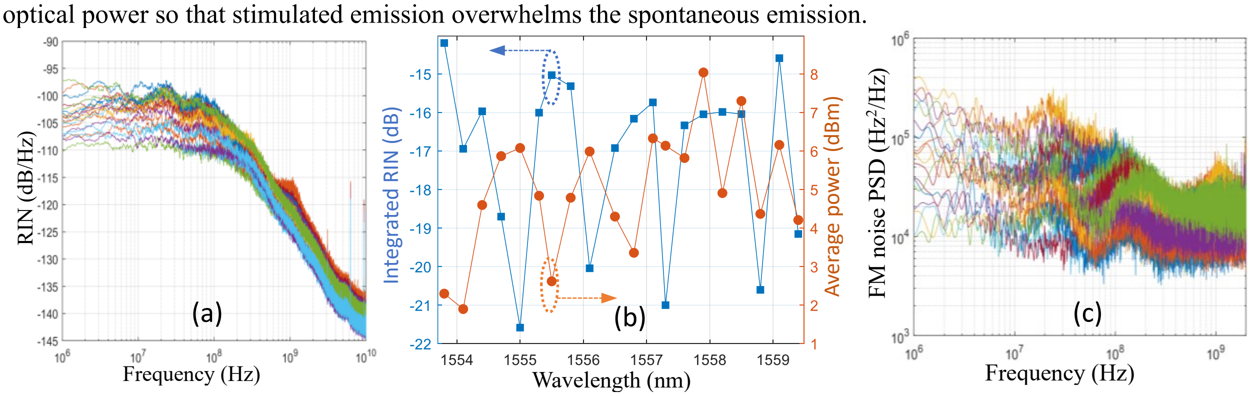

Fig.2. (a) RIN spectra of 20 individual spectral lines measured between 1553.8 nm to 1559.4 nm. (b) integrated RIN (left y-axis) and average power (right y-axis) of 20 spectral lines, and (c) FM noise power spectral density $S_{FM}(f)$ of the same 20 individual spectral lines

3. Coherent system performance

In order to evaluate the performance of the OFC laser source in system applications, we constructed a coherent fiber-optic system with the block diagram shown in Fig.3. The optical Tx is based on part of a commercial coherent transceiver (Ciena, *WaveLogic-Ai*) which was modified to allow the insertion of an external laser source. Because the optical power from the OFC laser exceeds the safe limit of the electrooptic modulator in the Tx, a WSS is used to select a single spectral line at a time to send to the Tx. In practical applications, an optical demultiplexer can be employed to separate spectral lines from an OFC laser source before sending them to a group of electrooptic modulators, alternately the modulators can be wavelength selective and arranged in series. Two digital subcarrier channels of differential coded 16-QAM signal each at 15 GBaud were modulated onto the lower and upper sidebands of each optical carrier. The modulated optical signal is transmitted through 78.3 km single mode fiber and detected by a coherent optical receiver, in which a tunable laser is used as the local oscillator (LO). A 1nm optical bandpass filter (OBPF) is used to remove broadband ASE noise from

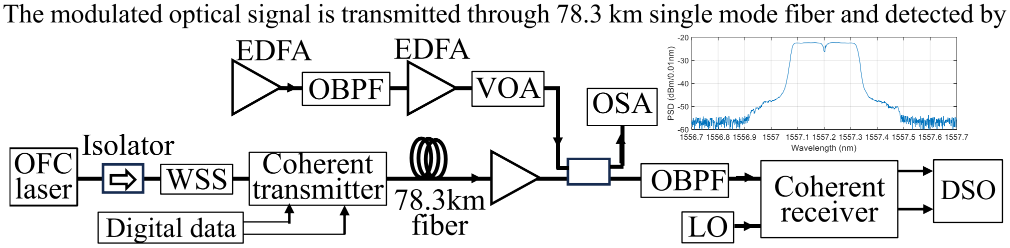

Fig.3. Experimental setup for system test. Inset: example of modulated optical signal spectrum of a spectral line.

optical amplifiers. 10% of the optical signal is tapped through a 2x2 optical coupler to monitor the OSNR. Extra optical noise can also be added to the receiver to investigate the BER versus OSNR characteristics. An example of modulated optical spectrum of each channel is shown in the inset of Fig. 3.

We measured the BER of all 20 channels in the wavelength window between 1553.8 nm and 1559.4 nm without noise loading in the receiver, as well as the corresponding OSNR of each channel as shown in Fig.4(a), where OSNR is defined with 0.1 nm noise bandwidth. Constellation diagrams of the channels with the highest and the lowest BER are also shown in the same figure. Channels with lower BER generally correspond to those with higher OSNR, but with a few exceptions which are attributed to the difference of the RIN levels. Nevertheless, BERs of all 20 channels measured in the experiment are lower than the HD-FEC threshold of 3.8×10^{-3}.

To investigate BER versus OSNR characteristics we loaded extra ASE noise into the receiver. Noise loading is accomplished with two EDFAs where the 2nd EDFA amplifies bandwidth limited ASE noise from the 1st EDFA, and a variable optical attenuator (VOA) is used to control the amount of noise loading to change the OSNR. Two channels corresponding to the highest and lowest RIN were chosen for the BER versus OSNR measurement. For comparison we also used a low-RIN external cavity laser (ECL) in place of the OFC laser for the BER versus OSNR measurement, and the results are shown in Fig. 4(b). The dashed line in Fig.4(b) provides the theoretical limit of differential coded 16-QAM signals at 30 GBaud symbol rate [6]. BER degradation from theoretical limit and BER floor of approximately 2×10^{-4} for the system using ECL can stem from the transceiver noise due to digitizing errors, I/Q skew, imperfections of transfer function equalization and carrier phase recovery [7]. Using ECL as the benchmark, Fig.4(b) shows that at a HD-FEC threshold of 3.8×10^{-3} the OFC laser source introduces approximately 2 to 3 dB additional OSNR penalties depending on the RIN level of each spectral line.

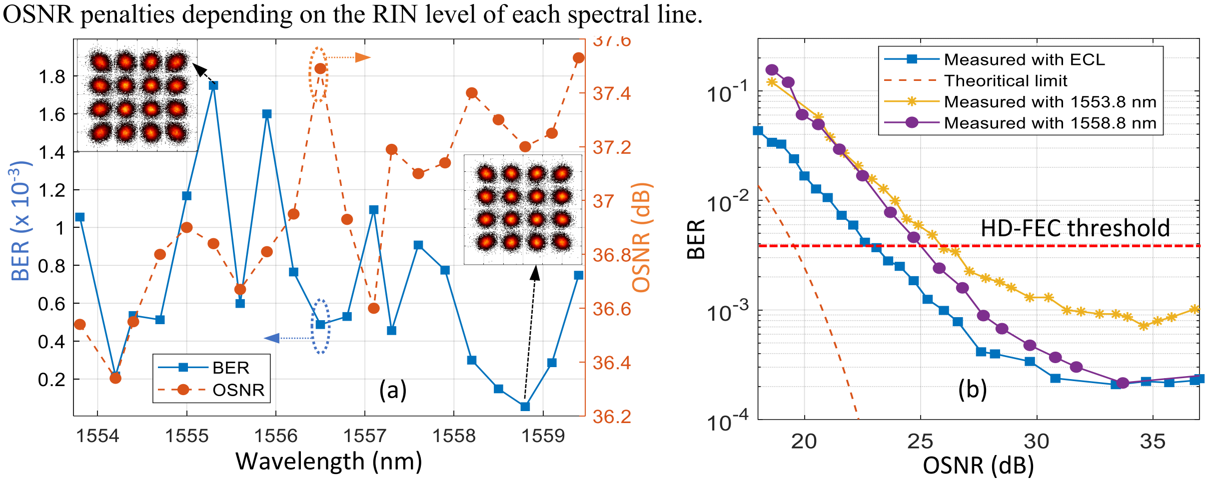

Fig. 4: (a) BER of 16QAM signals of 30GBaud for 20 spectral lines between 1553.8nm to 1559.4nm and OSNR of each spectral line. (b) Comparison of BER versus OSNR for using external cavity laser (ECL) and frequency comb laser as two wavelengths.

4. Conclusion

We have characterized a high-power multi-wavelength QW FP laser diode for coherent optical transmission. Transmission over 78.3 km single mode fiber was demonstrated based on this OFC laser source. 20 spectral lines were chosen giving a potential single polarization system capability of 2.15 Tb/s (4.3 Tb/s for dual polarization) when each line carries 16-QAM signal at a 30GBaud symbol rate.

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