42.8-Gb/s RZ-DQPSK transmission with FBG-based in-line dispersion compensation

42.8-Gb/s RZ-DQPSK Transmission With FBG-Based In-Line Dispersion Compensation

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***Abstract*—Phase ripple impairments induced through cascaded fiber Bragg gratings (FBGs) are discussed for 42.8-Gb/s transmission. We show the feasibility of transmission over 1140 km (12 × 95 km) using return-to-zero differential quadrature phase-shift keying modulation and FBG-only dispersion compensation. We further compare FBGs with dispersion-compensating fiber for dispersion compensation and analyze the influence of wavelength detuning.**

***Index Terms*—Differential quadrature phase-shift keying (DQPSK), dispersion compensation, fiber Bragg gratings (FBGs), optical communication, phase ripple (PR).**

I. Introduction

DISPERSION-COMPENSATING fiber (DCF) is currently used as the standard solution for group-velocity-dispersion (GVD) compensation in long-haul transmission links, since it yields colorless, slope-matched dispersion cancellation with negligible cascading impairments. However, DCF is limited in optical input power to avoid nonlinear impairments and has a relatively high insertion loss, which complicates link design.

Among the promising developments towards more cost-effective optical transmission systems are chirped multichannel fiber Bragg gratings (FBGs) for in-line dispersion compensation. Chirped FBGs have a negligible nonlinearity and low insertion loss [1], [2]. This potentially allows simpler, more cost-effective, erbium-doped fiber amplifier (EDFA) design by placing the FBG between the EDFA output and transmission fiber, omitting the need for interstage access. The main drawback of FBGs is that they suffer from distortions in their phase response, better known as group delay ripple (GDR) [3]. Fig. 1(b) depicts as an example the GDR of a typical FBG channel. The GDR is caused by imperfections in the gratings fabrication process. Improved fabrication processes have, however, gradually reduced the GDR of state-of-the-art slope-matched FBGs [4], such that for 10.7-Gb/s transmission FBG-based in-line dispersion compensation is an appealing alternative to DCF, up to approximately 2000 km [5].

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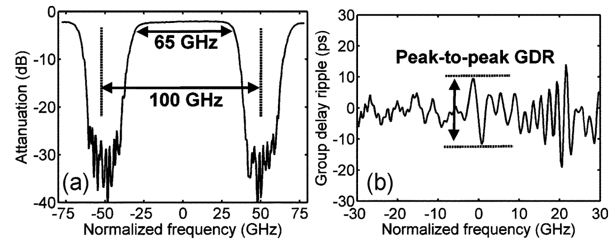

Fig. 1. (a) Amplitude response and (b) GDR of a typical FBG channel.

For future link upgrades (e.g., from 10.7 to 42.8 Gb/s per wavelength-division-multiplexing (WDM) channel), the FBG-induced penalty can still be a key concern since the higher line rate increases the associated penalty [6]. The FBG peak-to-peak ripple amplitude is a much larger fraction of the bit period for 42.8-Gb/s modulated signals in comparison to 10.7-Gb/s modulation. The ripple period on the other hand is usually well below the modulation frequency for 42.8-Gb/s modulated signals, which reduces the ripple impact [3]. Note that the best prediction of the penalty associated with cascaded FBGs is generally the phase ripple (PR) weighted by the signal spectrum [7]. For FBGs that have a channelized dispersion-compensation profile, as discussed here [see Fig. 1(a)], the broad optical spectrum can further increase the penalty because the FBGs incur narrowband filtering and have an increased PR near the edge of the passband. It is, therefore, advantageous to use a 42.8-Gb/s modulation format with a relatively narrow optical spectrum and longer bit period (in comparison to binary modulation formats), as for example return-to-zero differential quadrature phase-shift keying (RZ-DQPSK). The PR penalty is generally also smaller for phase modulated formats in comparison to amplitude modulation [8].

In this letter, we discuss the PR-induced penalties on long-haul 42.8-Gb/s transmission when FBGs are used for in-line dispersion compensation. We show that in combination with RZ-DQPSK modulation, a 1140-km transmission distance is feasible.

II. Experimental Setup

Fig. 2 depicts the recirculating loop setup. In this experiment, 32 distributed feedback laser outputs are combined on a 100-GHz ITU grid, from 1538.2 to 1563.0 nm. A 100-GHz channel grid is used here throughout the experiments because the channelized FBGs have a 100-GHz periodicity [Fig. 1(a)]. The RZ-DQPSK modulator chain starts with a Mach–Zehnder modulator (MZM), carving a pulse with a 50% duty cycle. The second modulator is an integrated DQPSK modulator [9]. A 21.4-Gb/s pseudorandom bit sequence with a length of $2^{15}-1$ is split in two and fed to both inputs of the 42.8-Gb/s DQPSK

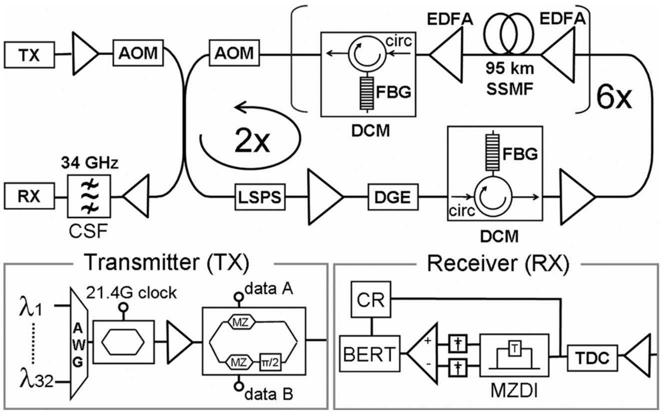

Fig. 2. Experimental setup. Circ: circulator. AOM: acoustic optical modulator.

modulator, with the second sequence being inverted and delayed over 10 bits for decorrelation.

The recirculating loop used in the transmission experiment consist of 6 × 95 km standard single-mode fiber (SSMF) spans. The average loss of the SSMF spans is 19.0 dB. EDFA-only amplification is used, with double-stage EDFAs to control the tilt of the WDM spectrum. The SSMF input power is ~0.5 dBm per WDM channel. Before the first span, an FBG-based dispersion-compensation module (DCM) with −1020 ps/nm of GVD (at 1550 nm) is used for precompensation, creating a double periodic dispersion map. The launch power into the DCF-based DCMs is ~7 dB reduced with respect to the SSMF launch power. Loop-induced polarization effects are reduced using a loop-synchronous polarization scrambler and power equalization of the dense WDM channels is provided by a channelized dynamic gain equalizer (DGE).

At the receiver, the desired WDM channel is selected using a narrowband 34-GHz channel-selection filter (CSF) and the residual GVD is per-channel optimized with a tunable dispersion compensator (DCF/SSMF-based) to minimize the bit-error rate (BER). After the CSF, the signal is split and one part is used for clock recovery. The other part is fed to a two-bit (94 ps) Mach–Zehnder delay interferometer (MZDI) to convert the signal from phase to intensity modulation, followed by a balanced detector. The use of a two-bit instead of a one-bit delay MZDI might result in slightly higher penalties [11]. The signal is demultiplexed to 10.7 Gb/s with a 1 : 2 demultiplexer and evaluated using a BER tester programmed for the expected bit sequence.

III. Experimental Results

To analyze the impairments resulting from the cascaded FBGs, the performance for all 32 WDM channels is measured after two circulations (1140 km). First, in-line dispersion compensation with only FBG-based DCMs is considered. The six in-line DCMs in the recirculating loop have either a GVD of −1345 ps/nm (5×) or −1681 ps/nm (1×). Hence, after two recirculations, a total number of 14 FBGs is cascaded. Fig. 3(a) depicts the measured Q-factor for all WDM channels. The PR penalty is clearly visible through the large (3.0 dB) spread in performance between the 32 WDM channels. Despite the significant PR-induced penalty, the measured Q-factor is for all channels above the forward-error-correction (FEC) limit of concatenated FEC code with 7% overhead (9.0 dB).

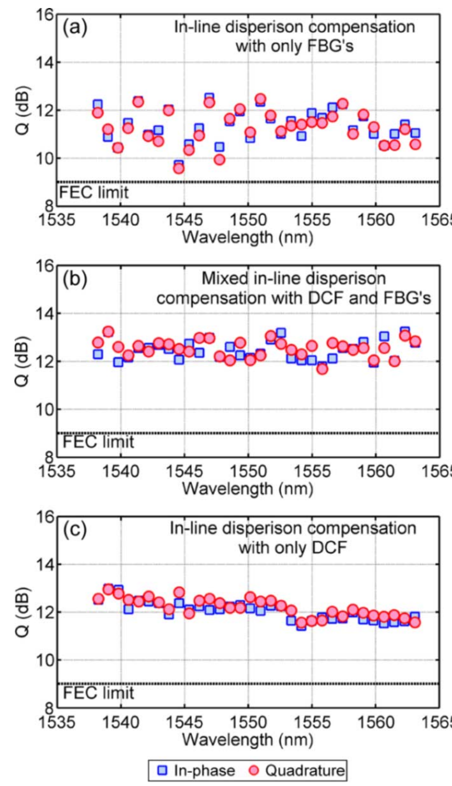

Fig. 3. Measured Q-factor for 32 WDM channels after 1140 km (12 × 95 km) of SSMF using dispersion compensation with (a) only FBGs, (b) mixed DCF and FBGs, and (c) only DCF.

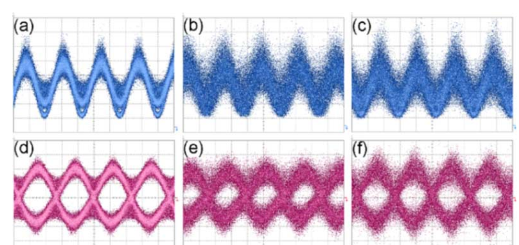

Fig. 4. Eye diagrams showing the signal before phase demodulation [(a)–(c)] and the quadrature tributary after demodulation [(d)–(f)]. Back-to-back [(a), (d)] and after 1140-km transmission for $\lambda = 1553.3$ nm [(b), (e)] and $\lambda = 1538.2$ nm [(c), (f)].

Fig. 4 shows eye diagrams before and after phase demodulation (quadrature tributary). The distortions in the back-to-back eye diagram before phase demodulation [Fig. 4(a)] result from narrowband filtering at the receiver. After transmission, the combination of residual dispersion and PR impairments results in a WDM channel dependent eye shape. The eye diagram in Fig. 4(e) shows a more severe PR penalty (Q-factor 11.2 dB) than the eye diagram in Fig. 4(f) (Q-factor 12.3 dB). Note that in the experiment the residual dispersion is optimized on a per-channel basis to minimize the BER. The measured difference in optimal postcompensation between the channels shown in Fig. 4(e) and (f) is approximately 220 ps/nm. This indicates that optimizing the residual dispersion can be used to reduce the PR associated penalty [8], [10]. In deployed systems, this would require per-channel tunable dispersion compensation at the receiver, for example, through the use of a thermally tuned

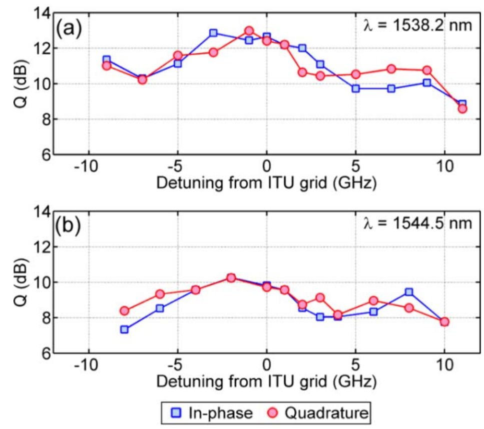

Fig. 5. Measured Q-factor versus wavelength detuning from the ITU grid after 1140 km, for the WDM channels at (a) 1538.2 and (b) 1544.5 nm.

FBG [6]. In the absence of PR impairments, the residual dispersion would normally be close to zero [9].

Next, every second FBG-based DCMs is replaced with DCF-based DCMs and the measured performance for all WDM channels is depicted in Fig. 3(b). The in-line dispersion compensation now consist of FBG-DCMs (-1345 ps/nm, $3\times$) and DCF (-1512 ps/nm, $3\times$). The smaller number of cascaded FBG clearly improves the transmission performance. The spread between the WDM channels is reduced to 1.5 dB and the average Q-factor is increased to 12.5 dB, resulting in nearly a 3-dB margin with respect to the FEC limit.

Finally, Fig. 3(c) shows the measured performance when all FBG-DCMs are replaced by DCF except for the precompensation DCM. The in-line dispersion map consists now of DCF modules with either -1345 ps/nm ($3\times$) or -1512 ps/nm ($3\times$) of GVD. The average Q-factor is with 12.1 dB slightly lower in comparison to the mixed FBG/DCF in-line dispersion compensation. The measured Q-factor shows a performance difference between the lower and higher part of the WDM spectrum. We conjecture that this is the result of increased nonlinear impairments in the DCF due to a tilt in the WDM spectrum, which increases the power in the higher part of the WDM spectrum. This illustrates that FBG-based inline dispersion compensation can simplify EDFA spectral tilt control. The spread between adjacent WDM channels is reduced to approximately 1 dB.

IV. Wavelength Detuning

The performance in Fig. 3 depicts the measured Q-factor when the WDM channel is centered on the ITU grid, whereas PR penalties can change significantly with only a small change in center wavelength [12]. Fig. 5 depicts the measured Q-factor as a function of the wavelength detuning. Note that the channelized DGE used in the recirculating loop has a 42-GHz 3-dB bandwidth and the detuning range is, thus, not limited by the channelized FBGs. To measure the penalty as a function of wavelength detuning, both the wavelength of the transmitter laser and the center wavelength of the receiver-side CSF are changed. Fig. 5(a) shows the measured Q-factor for the channel at 1538.2 nm, which suffers only from a small PR penalty, whereas the channel at 1544.5 nm is severely affected [Fig. 5(b)]. Both channels show, however, that the PR penalty can easily change with up to 3 dB within a $+/-5$-GHz detuning range. Note though that a typical laser wavelength drift over the system lifetime would be $+/-1.5$ GHz.

As evident from Fig. 5(b), the measured Q-factor drops below the FEC limit within the detuning range. The PR-induced penalty is, however, artificially enlarged in these experiments because each of the FBGs is passed twice within the recirculating loop. The peak-to-peak PR increases linearly when the same FBG is passed multiple times, whereas it increases statistically (square-root) when independent FBGs are cascaded, as occurs in field deployment [12]. Hence, the peak-to-peak PR will be 40% higher for a recirculating loop with two recirculations in comparison to a straight line.

V. Conclusion

We compared FBG-only, mixed FBG/DCF, and DCF-only in-line dispersion compensation, which shows the potential impact of FBG-based in-line dispersion compensation on 42.8-Gb/s RZ-DQPSK transmission. Long-haul transmission with only FBGs for in-line dispersion compensation might not be feasible considering the small margins available with 42.8-Gb/s transmission. However, a smaller number of FBGs (up to $\sim$10) result in an acceptable PR-related penalty, which is comparable to or smaller than the increased nonlinear penalty when DCF is used for in-line dispersion compensation. However, tunable dispersion compensation at the receiver is desirable to reduce the impact of PR impairments.

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