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Investigation of performance variations due to the amplitude of group-delay ripple in chirped fiber Bragg gratings

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Abstract

We measure the system impacts due to the amplitude of group-delay (GD) ripple in single and cascaded chirped fiber Bragg gratings (CFBGs). Signals with smaller pulse width result in smaller performance variation at the same data rate. A 65-ps peak-to-peak GD ripple induces 0.9, 1.7, and 2.7 dB maximum penalties for 10, 20, and 40-Gb/s, respectively. We also find that cascading gratings with random ripple causes much less degradation than cascading gratings with the same ripple profile.

Keywords: Optical communications; Fiber Bragg grating; Dispersion compensation; Group-delay ripple

1. Introduction

Nearly all ⩾10-Gb/s/channel systems require the periodic management and compensation of fiber chromatic dispersion. The most common type of deployed chromatic dispersion compensator is dispersion compensating fiber (DCF). Another potential alternative is the use of dispersion-compensating chirped fiber Bragg gratings (CFBGs), for which the reflection time delay (ps) is a function of wavelength (nm) [1–10]. Such gratings have the potential for the following characteristics: (i) fixed or tunable operation, (ii) single- or multiple-channel functionality, (iii) low nonlinearity, (iv) compact footprint, (v) low loss, and (vi) compensation for dispersion slope of the transmission fiber.

Unfortunately, the fabrication process of CFBGs is not perfect and produces random "ripples" in the group delay (GD) performance of the grating. These ripples adversely affect the quality of the compensated signal and limit the utility of CFBG-based solutions. The effects of ripple depend on the peak-to-peak and root-mean-square (RMS) values as well as the ripple frequency in relation to the signal bandwidth. Although previous reports, either theoretical or experimental, about systems effects due to GD ripple have elucidated several issues [11–17], actual system measurements of the relationship between ripple values and system power penalties are still quite interesting to network designers, especially the cascading effects, which would be encountered when using CFBGs as periodic in-line compensators. In addition, the impacts on different data rates and data formats will also provide useful information for the performance evaluation and optimization.

In this paper, we experimentally show the system performance variations due to group-delay ripple, specially, the amplitude (both peak-to-peak and RMS values), when considering a single CFBG and cascaded CFBGs. We find that, for single gratings with different GD ripple, shorter pulse-widths (50-ps RZ and 10-ps RZ) can reduce the penalty induced by GD ripple, meanwhile, the impact of ripple becomes more and more serious as the data rate increases (10/20/40-Gb/s), e.g., the maximum power penalties are ∼0.9, 1.7, 2.7 dB after dispersion compensation with the same grating for 10, 20, and 40-Gb/s RZ data stream with ∼10-ps pulse width, respectively. For cascaded CFBGs, cascading the same grating results in similar performance as the ripple adds up linearly. However, cascading several gratings with random ripple does not degrade system performance much since the ripple growth obeys a square root law as the number of gratings increases, e.g., cascading one grating with 47-ps GD peak-to-peak ripple three times gives maximum power penalty of ∼6 dB, while when this grating is

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cascaded with three different gratings with peak-to-peak ripples of 72, 80, and 102 ps, the maximum power penalty is only ~3.4 dB within the grating bandwidth.

In addition, we also perform computer simulation to confirm our experimental results. Assuming that the frequency response of a CFBG within its passband is given by

$$H(\omega) = e^{i\Phi(\omega)},$$
$$\Phi(\omega) = \int \tau_g(\omega)\, d\omega = -\frac{2\pi c}{\lambda^2} \int \tau_g(\lambda)\, d\lambda,$$

where $\tau_g(\lambda)$ is the measured group-delay response of the CFBG, we can calculate the power penalty caused by the group-delay ripple for systems using an optically pre-amplified receiver based on the frequency response of the CFBG measured in our experiments.

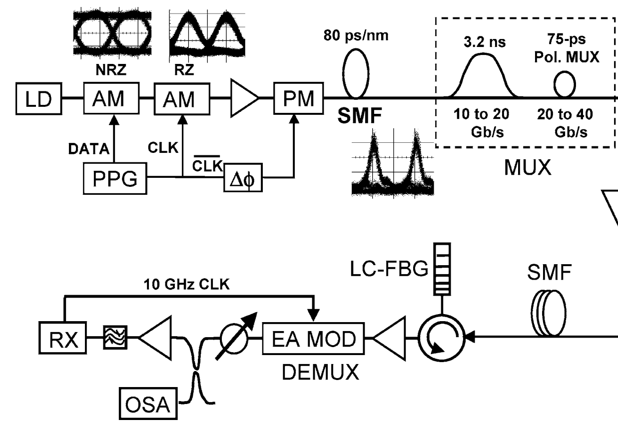

Fig. 1. Experimental setup for single chirped fiber Bragg grating (CFBG) testing. PPG: pulse-pattern-generator; AM: amplitude modulator; PM: phase modulator; LC-FBG: linearly chirped fiber-Bragg-grating; OSA: optical spectrum analyzer.

2. Single CFBG

The ripple in reflectivity (amplitude ripple), the period and amplitude of GD ripple are all key parameters for the system performance. Some analysis or preliminary experimental results have illustrated the effects of GD ripple frequencies [12,13,17]. A common rule for system designers is that systems would experience worst case as the ripple periods are comparable to the transmission bit rate, otherwise the data can effectively average ripples with shorter periods (i.e., higher frequencies). Although the period of GD ripple is an important parameter for assessing performance degradation, it is difficult to compare different periods due to the uncertainty of fabrication. Since the gratings used in our experiments have similar much shorter ripple periods to have limited effects at a data rate >10-Gb/s/channel, we assume the magnitude of GD ripple is the major goal for use to consider for the performance variations.

Through our experiments, all the grating ripple measurements are performed using a commercial dispersion analyzer (Agilent 86038) based on modulation phase-shift (MPS) method [18]. The modulation frequency is set to 2 GHz, the wavelength step is 2.5 pm, and the time resolution is 1 ps. The gratings used in measurements have similar characteristics: ~0.8 to 1-nm bandwidth, <3-dB amplitude (reflectivity) ripple, ~5-cm in length, and more important, with similar ripple frequencies (much narrower than transmission data pulses). Meanwhile, the polarization-mode-dispersion (PMD) values of all these gratings are less than 3 ps over the bandwidth, which is negligible for 10-Gb/s data rate.

Figure 1 shows the experimental setup for different data rate (10, 20, and 40-Gb/s) and data formats (NRZ and RZ). The 10-Gb/s NRZ signal is generated by applying the bit stream with $2^{23} - 1$ PRBS on an amplitude electrooptic modulator, and the 10-Gb/s RZ signal with 50% duty cycle (i.e., 50-ps pulse width) can be obtained after another amplitude modulator (AM) driving by the clock signal. This RZ signal is further compressed down to 10 ps through a phase modulator (PM) followed by 80-ps/nm of standard single-mode-fiber (SMF) (i.e., through the interaction between the signal chirping and fiber dispersive effect) [19]. Typical eye diagrams for 10-Gb/s NRZ, RZ (50-ps), and RZ (10-ps) pulses are inserted in the setup for reference. A two-stage optical multiplexer (MUX), is used to generate the 20 and 40-Gb/s RZ data streams. The first stage is a regular optical time-division-multiplexer with a 3.2-ns delay to generate the 20-Gb/s signal, while the second stage is a polarization interleaver using one piece of polarization-maintaining (PM) fiber to further provide a 40-Gb/s data stream. Only the RZ pulse trains with 10-ps pulse width are used for 20 and 40-Gb/s transmission. After transmission, an optical feedback loop to recover the 10-GHz clock from the data stream is used at the receiver end, and 10-Gb/s data stream is regenerated after demultiplexing (DEMUX) the 40 or 20-Gb/s data through an electro-absorption (EA) modulator electrically driven by the recovered 10-GHz clock. The EA modulator will perform pulse carving to sample the 40 or 20-Gb/s data streams to 10-Gb/s for regular detection. For all the data rates and data formats, the power penalty measured at 10^{-9} bit-error-rate (BER) after transmission over SMF and the grating compensator is compared with the back-to-back sensitivity. An optical pre-amplifier is used before the receiver to increase its sensitivity. Note that for 10-Gb/s data transmission, the multiplexing and demultiplexing parts have been bypassed and the back-to-back sensitivities of 10-Gb/s NRZ and RZ formats in our system are −32 and −34.5 dB m, respectively. We measure the penalties over the bandwidth of the gratings by varying the signal wavelength with a less than 0.01-nm step size. The statistical values (RMS or maximum) are then derived from the measured penalties.

First we measure the impact of GD ripple for different pulse widths at a 10-Gb/s data rate, as shown in Fig. 2a, and the corresponding maximum and RMS power penalties for both RZ and NRZ data formats are shown in Figs. 2b and 2c. Four CFBGs with different peak-to-peak ripple (47, 65, 103, 165-ps) are used for comparison. The results show that shorter pulse widths lead to lower power penalty, as well as smaller performance variation. This is mainly due to the fact that wider optical spectrum of the shorter pulse will have averaging effects on the high frequency ripples, as mentioned previously and also pointed in Refs. [13,17].