Fast Digitally Variable Differential Group Delay Module Using Polarization Switching

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Abstract: We demonstrate the first compact, programmable differential-group-delay (DGD) module based on polarization switching. With a unique binary tuning mechanism, the device can generate any DGD value from –45 ps to +45 ps in <1 ms with a resolution of 1.36 ps. The device exhibits negligible transient-effect induced power penalty (<0.2 dB) in a 10-Gb/s NRZ system.

OCIS codes: (060.2330) Fiber optics communications, (060.2340) Fiber optics components, (060.2360) Fiber optics links and subsystems.

1. Introduction

Differential-group-delay (DGD) is characterized as the relative delay time between two orthogonal polarization states. Tunable DGD provides superior performance in: (i) statistical polarization mode dispersion (PMD) emulation, (ii) dynamic PMD compensation, (iii) bit-alignment in time-division-multiplexing (TDM) systems by proper polarization control, and (iv) microwave signal processing and phased array radar beam forming when the device is used as a true time delay [1].

PMD has become a critical challenge for high data rate systems [2], thereby requires dynamic compensators. Variable DGD in PMD compensators can reduce the risk of feedback loops trapping in a locally optimized state and provides superior performance as compared to fixed ones [3][4]. In addition, for PMD compensators using polarization scrambling at the transmitter to reduce the complexity and increase the stability of the feedback control, a variable DGD must be applied to exactly cancel fiber's first-order DGD [5]. Finally, as higher-order PMD effects become significant for pure first-order compensators to handle, variable DGD becomes even more critical for the higher-order PMD compensation [6-8].

Previous approach of making variable DGD element is to introduce a relative delay between two orthogonal polarization components after physically separating them with a polarization beam splitter. The two polarization components are then recombined with a polarization beam combiner [4]. Such a device has low speed (sub-second), large output polarization fluctuation, large footprint, and poor control certainty due to mechanical motion.

In this paper, we demonstrate the first programmable DGD module based on a novel polarization switching approach. Without any moving part, the device can generate any DGD values from –45 ps to +45-ps in less than 1 ms. The unique digital tuning mechanism ensures a precise and repeatable delay control with 1.36-ps (6-bit) resolution (0.1 ps resolution can be readily achieved by design). We show that this precise and repeatable DGD generation capability can be used to generate any DGD distribution with tunable average values for first-order PMD emulation. Such a high-speed emulator may be desirable for evaluating PMD compensators. Finally, we show that in addition to excellent static performance, such as low insertion loss (<1.4 dB), low PDL (<0.2 dB), and small higher-order PMD (< 85 ps^2), the device has negligible transient effects on system performance and therefore is a suitable candidate for PMD compensation.

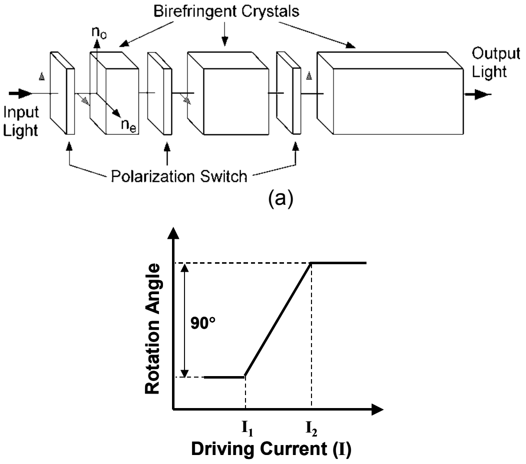
2. Programmable DGD

The tunable DGD module employs polarization-switching approach to generate different delays [1]. As shown in Fig. 1(a), the device consists of multiple switch/delay sections. Each switch/delay section consists of a birefringent crystal and a magnetooptic (MO) polarization switch. The lengths of the birefringent crystals are arranged in a binary power series, increasing by a factor of 2 for each section. Such a binary arrangement requires minimum crystal sections for the highest delay resolution. The typical response curve illustrating the binary nature of the MO switch is shown in Fig. 1(b). Assuming that the smallest birefringent crystal length is ℓ, we define a unit delay time $\Delta\tau_d$ to represent the delay generated by the shortest delay section. Using $\Delta\tau_d$ to represent the generated total DGD, we obtain

$$\delta\tau = \left|(n_e - n_o)\frac{\ell}{c}\right|, \qquad \text{and}$$

$$\Delta\tau_d = -\delta\tau \sum_{n=1}^{6}(-1)^{b_n} 2^{n-1}$$

where n_o and n_e are the ordinary and extraordinary index of refraction, c is the speed of light, n is the number of sections (bits), and b_n=0, 1 is the binary value of the n^{th} bit, determined by the polarization switch associated with the n^{th} bit. It is evident from the equation that for the 6-bit device, total 64 DGD values from -63 δt to +63 δt can be generated with a resolution of 2 δt.



(a) (b)

Fig. 1 (a) Illustration of a programmable DGD based on polarization switching. (b) Typical response curve of a magnetooptic polarization switch.

Based on Fig. 1, a novel programmable DGD element is demonstrated. We use 6-section birefringent crystals that can generate tunable DGD values from –45 ps to +45 ps with 1.36-ps resolution (2δt .. We carefully measured static performance of these devices and found that the insertion loss of the device is typically less than 1.4 dB, PDL less than 0.25 dB, and wavelength dependent loss less than 0.2 dB across the C band (1530-1560 nm). The DGD varying speed ranges from 0.1 ms to 0.6 ms, depending on how many bits are involved in switching. To verify the accuracy of designed DGD states, we used a commercial PMD analyzer to measure both the DGD value and second-order PMD at each logic DGD state. As shown in Fig. 2(a), the measured DGD values agree well with designed DGD values. Equally important, the second-order PMD is very small, less than 85 ps^2, even at high DGD values. This 2nd-order PMD value is comparable with that of a polarization-maintaining (PM) fiber of a similar DGD value.

The precise and repeatable DGD generation capability of our DGD module is also ideal for generating a series of DGD values with any statistical distribution for a given number of samples. We therefore developed a software to control the DGD module to generate statistical DGD samples with Maxwellian distribution with a selectable average DGD value, i.e. tunable average DGD value can be obtained according to a desired distribution. Fig. 2(b) shows the measured distribution for 500 samples that has an average value of 10ps. Although such PMD emulation is only of first-order (almost no higher-order effects involved), its high speed and precise feature should prove powerful in evaluating the dynamic performance of PMD compensators.

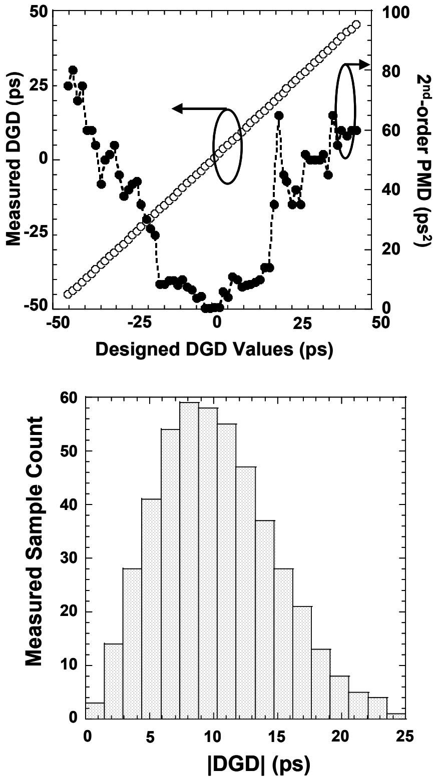


Fig. 2 (a) Measured DGD and second-order PMD as a function of designed DGD. (b) Repeatable DGD generation is used to generate dynamic first-order PMD distribution with tunable average values. Here the average DGD is 10ps for 500 samples.

3. Dynamic Performance

For continuous data traffic network applications, it is critical that the system performance be unaffected during DGD state switching. Therefore, the DGD module must have a well-controlled dynamic performance. In our experiment, we first characterized the switching effect on the DGD value. In principle, when the device is switched from one DGD state to another, the DGD value will change from one value to another precisely. However, because the device has finite switching speed, the DGD value during switching is different from either the starting or ending states. When the device is switched in smallest step, the maximum DGD value excursion from the DGD value of the ending state is defined as the transient DGD. Because it is difficult to directly measure the transient DGD during switching due to the limited response speed of the measurement instrument, we used a quasi-static measurement method. Instead of having a full 90° polarization rotation in one step to change the DGD value from one state to another, we incrementally increase polarization rotation angles in steps of a few degrees while measure the corresponding DGD with a commercial polarization analyzer. We repeat the procedure for all DGD values from 0 ps to 45 ps in steps of 1.36 ps and the results are shown in Fig. 3(a). The insert shows the detailed DGD values between two adjacent DGD states. It is evident that the transient DGD is always less than the step size. The small transient DGD is important for using the device in PMD compensators.

In order to test the system impacts during fast switching, we integrate the DGD element into a 10-Gb/s NRZ transmission link modulated at 2^{31}-1 PRBS. The input optical-signal-to-noise-ratio (OSNR) to the DGD module is set to 30 dB (0.1 nm bandwidth). An optical pre-amplifier before the receiver is used to increase sensitivity. The system's back-to-back sensitivity is measured to be -31 dBm. Power penalties are measured by comparing the receiver sensitivity of the system at a 10^{-9} bit-error-rate (BER) with the back-to-back sensitivity. We measured two cases: (i) power penalties at static DGD states, and (ii) power penalties when neighboring states are jogging back and forth at 1 kHz (1 ms continuous switching). As shown in Fig. 3(b), a negligible power penalty of < 0.2 dB due to fast polarization switching (jogging) was obtained. This feature enables the applications of DGD element in either PMD emulation and compensation or microwave photonic networks.

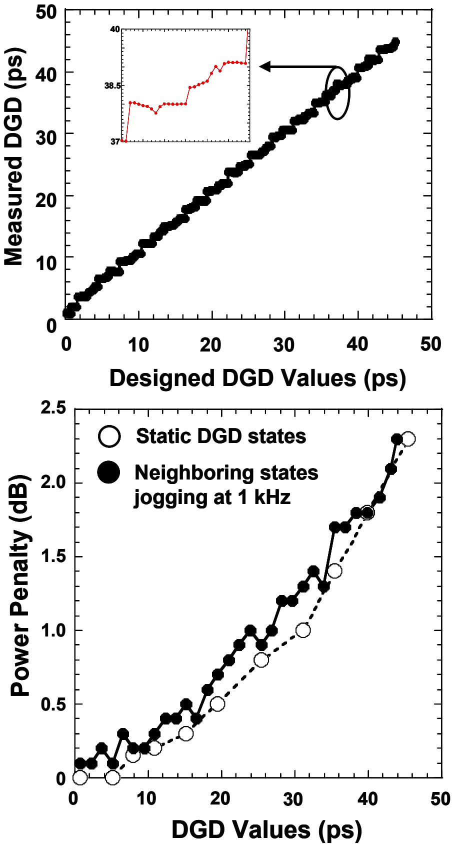


Fig. 3 (a) Measurement of transient DGD by equivalent small polarization variation between different DGD values from 0 to 45ps. (b) Power penalties measurement. Open circle: DGD module remains static after changing state. Solid circle: DGD module keeps jogging back and forth between neighboring states at 1 kHz in a 10-Gb/s NRZ (2^{31}-1 PRBS) link.

In conclusion, we demonstrated the first digitally variable DGD module based on polarization switching with both excellent static and dynamic performances, as well as its feasibility in high-speed network application.

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