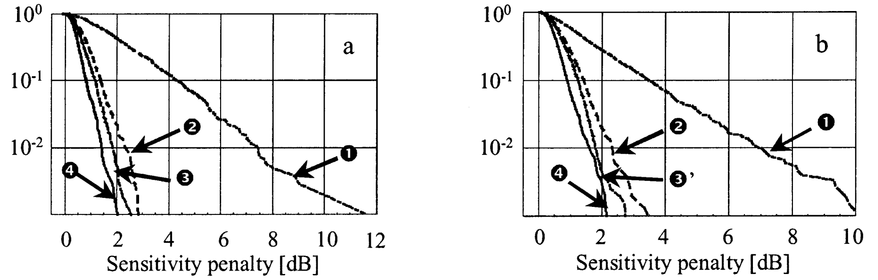

WQ3 Fig. 2. Experimental (a) and numerical (b) cumulative probabilities of sensitivity penalty. The emulated PMD is 39 ps. 1 W/o comp.; 2 W/simple first-order comp.; 3 Transient-state during comp.; 3′ Absolute max tracking comp.; 4 ISOP control + first-order comp.

pensation based on local maximum tracking, with compensation based on absolute maximum tracking and with compensation using ISOP control. The improvement brought by the latter in comparison with an absolute maximum tracking is obvious even if slight. Figure 3 plots DOP versus DGD with and without compensation. The advantage of the relevant ISOP control lies in the removal of the residual worst cases that appears for total DGD greater than 60 ps. Thanks to this new scheme of compensation the tolerable PMD increases up to 37% of the bit-time (obtained by extrapolation).[4]

Actually the issue of sub-optimum, in the case of these high-DGD conditions, steps from higher-order effects which make the maxima of the function DOP(Ω_C) not to be equivalent and make the system wander slightly from PSP alignment. To this regard the degree of freedom brought by PC1 is used to decrease the second-order effects. Indeed Figure 4 shows that these cases undergo the most important fading of the second-order parameter in comparison with ones of low DGD which seem to remain the same. The trade-off between PSP alignment and second-order is not so tight and becomes in favor of the former, leading to a better DOP.

5. Conclusion

A new scheme of compensation combining first-order compensation and relevant ISOP control was proposed. Its interest lies in the fact that it avoids staying a long time on sub-optimum, yielding poor performance of the compensator. It has proved to be a good and a simple means to improve the value of tolerable PMD in the line up to 37% of bit-time.

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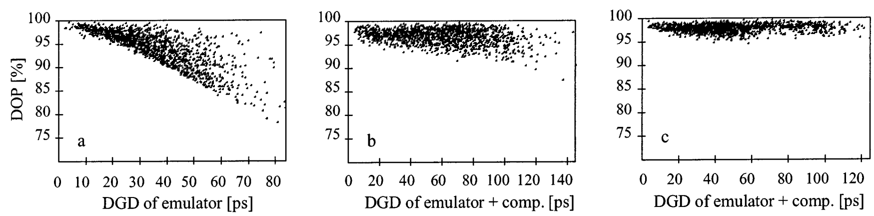
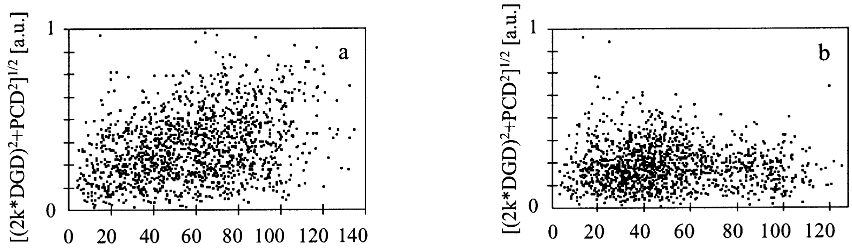


WQ3 Fig. 3. Numerical assessment of DOP versus total DGD for three cases: without compensation (a), with first-order compensation (b) and with first-order compensation and ISOP control (c).



WQ3 Fig. 4. Second-order parameter $[(2k^*DGD)^2 + PCD^2]^{1/2}$ versus total DGD in the case of first-order compensation (a) and ISOP control with first-order compensation (b).

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WQ4 4:45 pm

Combating PMD-induced signal fading in SCM optical systems using polarization diversity optical receiver

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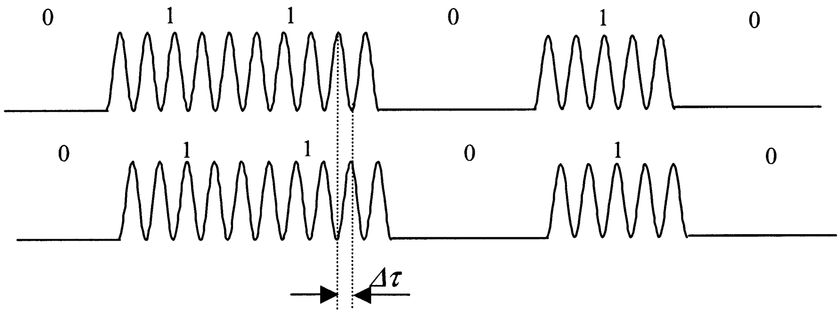
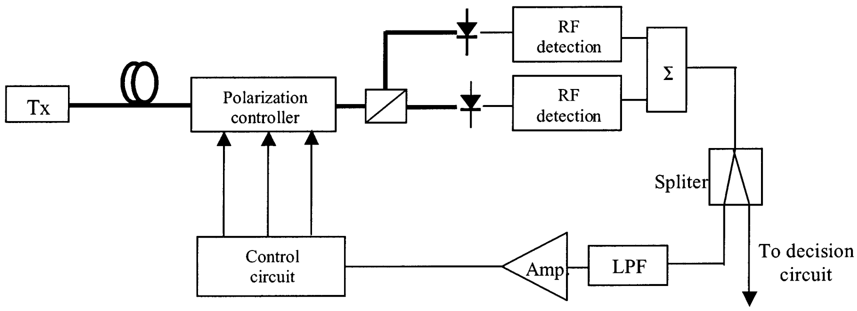
Optical sub-carrier multiplexing (SCM) is a modulation scheme where multiple signals are multiplexed in the RF domain and transmitted on a single optical carrier. A significant advantage of SCM is that microwave devices are more mature than optical devices: the stability of microwave oscillators and the frequency selectivity of microwave filters are much better than their optical counterparts. While a popular application of SCM technology is analog CATV distribution,[1] SCM is also considered for use in high-speed digital transmission because of its flexible bit rate granularity and bandwidth efficiency.

In high-speed long distance optical transmission using SCM, in order to minimize the impact of fiber chromatic dispersion, optical single-sideband (SSB) modulation has been used which also increases the optical bandwidth efficiency.[2] In this case, system tolerance to chromatic dispersion depends on the data rate on each individual sub-carrier channel. However, the impact of PMD is mainly determined by the frequency of each RF sub-carrier because the subcarrier frequency is usually much higher than the datarate it carries. Fig. 1 illustrates the waveforms of a binary coded SCM signal along the fast and the slow principal states of polarization (PSPs) of the fiber, respectively. Adding these two PSP components on the photodiode, a complete signal fading may occur when the differential group delay (DGD) approaches half of the RF sub-carrier period. PMD-induced carrier fading happens to both double sideband and single sideband modulated optical SCM signals,[3] and it is one of the biggest problems which prevents long distance applications of optical SCM systems.

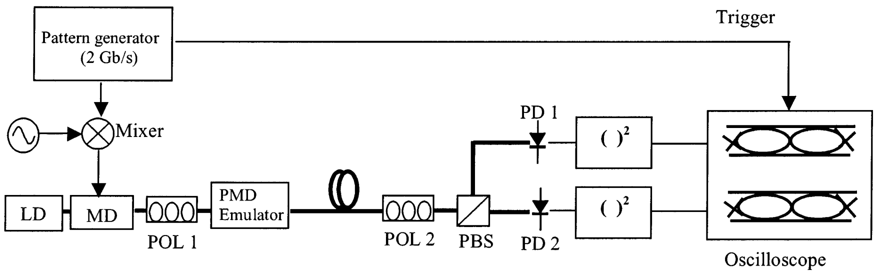
PMD compensation is currently an active area of fiber-optic system research. In many PMD compensator systems[4,5] a polarization beam



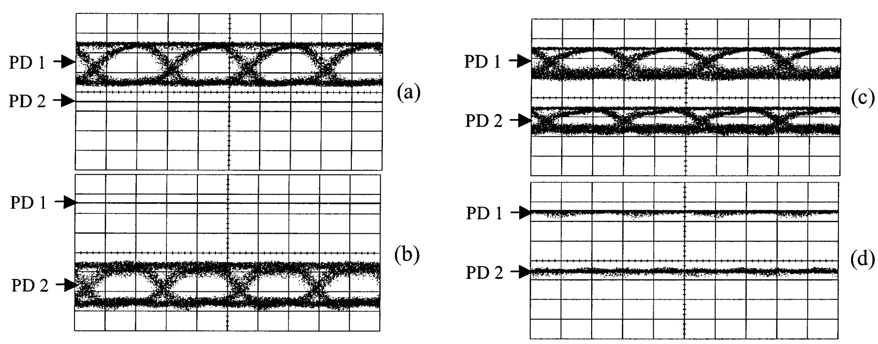
WQ4 Fig. 1. Illustration of signal waveform of an SCM system carried by two PSPs of the optical fiber.



WQ4 Fig. 2. Block diagram of PMD insensitive optical receiver using polarization diversity



WQ4 Fig. 3. Measurement setup. LD: laser diode, MD: optical modulator, POL: polarization controller, PBS: polarization beam splitter, PD: photodiode, ()^2: square-law detector.



WQ4 Fig. 4. Measured eye diagrams at the two photodiode branches.
(a) PBS aligned with fiber PSP, signal SOP aligned with the fast PSP
(b) PBS aligned with fiber PSP, signal SOP aligned with the slow PSP
(c) PBS aligned with fiber PSP, signal SOP is in the middle between the fast and the slow PSPs
(d) PBS is in the middle between the two fiber PSPs.

splitter (PBS) is used to separate the signals on the two PSPs. A polarization controller (PC) precedes the PBS to align the PSPs with the principal axes of the PBS. Following the PBS is a variable delay line to compensate for the link DGD. Finally the two optical paths are recombined and the effects of PMD have been compensated entirely in the optical domain. Continuous monitoring of the residual PMD can be derived from the signal to provide feedback signal parameters for controlling the PC and the variable delay line. In such a system, the variable delay line is often implemented using a mechanical system to provide the needed DGD range. The speed, size, and reliability of this mechanism are raise concerns.

In order to eliminate PMD-induced carrier fading in SCM systems, we propose to use a polarization diversity optical receiver as shown in Fig. 2. In this setup, two photodiodes are used to detect the two PSP components at the output of the system. In order to ensure the alignment between the principal axis of the PBS and the PSP of the fiber, a polarization controller is used before the PBS. If the principal axis of the PBS is properly aligned with the PSPs of the optical fiber system, the amplitude of signals detected by both photodiodes will not be affected by PMD. The effect of PMD will be shown as a relative time delay between the waveforms carried by the two PSP components.

To verify the concept, an experiment was conducted using a setup shown in Fig. 3. A 2-Gb/s pseudo random NRZ signal was mixed with an 8-GHz RF carrier, this composite signal was used to drive an external modulator. A 62.5-ps DGD was created by a PMD emulator. Two polarization controllers were used in the system: the first controller (before the emulator) was used to adjust signal SOP and the second controller (after the emulator) was used for the alignment between fiber system PSP and the principal axis of the PBS. A dual-channel oscilloscope was used to display the waveforms detected by both photodiodes.

When the principal axis of the PBS is aligned with fiber system PSP, PMD does not distort the signal waveforms, but the amplitude of the waveforms detected by each photodiode depends on the signal SOP. Fig. 4(a) and (b) show the detected waveforms when the signal SOP is aligned with the fast and the slow PSP, respectively, and Fig. 4 (c) shows the waveforms when signal SOP is in the middle between the two PSPs. In this measurement, even though the amount of system DGD is 62.5-ps, which is equal to a half period of the RF carrier, the sum of the signal eye diagrams detected at the two receiver arms remain independent of the signal SOP. Because of the square-law detection after each photodiode, which eliminates the RF carrier, carrier fading can no longer happen when combining signal waveforms of the two branches.

On the other hand, if the principal axis of the PBS is not aligned with the fiber system PSP, PMD-induced carrier fading would happen at both of the two detection arms. Fig. 4(d) shows the detected waveforms when principal axis of the PBS is set in the middle between two fiber PSPs. In this worst case a complete carrier fading happened.

In conclusion, we have demonstrated a carrier fading free optical receiver for SCM optical systems using polarization diversity. Since a tunable optical delay line is not required in this setup, it may be more practical than optical domain PMD compensation.

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WQ5 **5:00 pm**

Optical compensation of PMD-induced power fading for single sideband subcarrier-multiplexed systems

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1. Introduction

Polarization mode dispersion (PMD), caused primarily by the random birefringence of single-mode optical fiber, is a critical challenge in the transmission of high speed digital baseband channels (≥10 Gbit/s). A key feature of PMD is its statistical behavior, since the relative orientation between the state-of-polarization (SOP) of the input signal and the principal-states-of-polarization (PSPs) of the fiber varies randomly with time. Moreover, the differential group delay (DGD) between the fast and slow PSP, i.e. first-order PMD, is a random process with a Maxwellian probability distribution. Note that even for very-low-PMD fiber, there is still an accumulation of PMD caused by small contributions of many in-line components.

Subcarrier multiplexing has several important applications in optical systems, including: cable television, antenna remoting, LANs, and header control information for packet-switched networks. Importantly, it has been reported that the transmission of analog and digital subcarrier-multiplexed (SCM) signals over fiber will also be severely affected by PMD.[1,2] For example, in 40-GHz optical SCM systems, the RF power is completely faded with ~12.5-ps instantaneous DGD. The deleterious PMD-induced power-fading effect in SCM is as follows. The DGD between the fast and slow PSP of an optical sideband in a SCM signal causes a phase difference in the corresponding received subcarrier signals in the photodetector. Superposition of the photo-currents may lead to serious power fading of the recovered subcarrier signal due to destructive interference that is a function of subcarrier frequency and accumulated DGD.[3] Furthermore, higher-order PMD can cause additional distortion and degradation of the transmitted signal.[4,5] Although single sideband (SSB) SCM system is relatively immune to chromatic dispersion, the PMD-induced RF power fading remains as an important problem.[2]

For many system conditions, robust transmission of an SCM data channel or tone necessitates the use of some type of technique to compensate or mitigate the power fading effects of PMD. One published method of compensation used a typical first-order PMD compensator, which consists of a polarization controller, a differential-group-delay element, and a monitoring feedback loop.[2] However, that method was limited since real PMD is far from being first order and has many higher-order components.[4,5] Moreover, that technique was valid only for a specific average link DGD.

We experimentally demonstrate a novel technique for compensating the PMD-induced power fading that occurs in single sideband SCM transmission systems. PMD-induced power fading can be understood in the optical domain as caused by the polarization state of the optical carrier being different from that of the SSB. After transmitting through a fiber link with PMD, we split the optical carrier and SSB signal, realign their polarization states to each other, and then combine them at the receiver. Thus the first-order and higher-order PMD-induced RF power fading could be completely compensated. Our experiment shows that RF power fading was compensated to be less than 1.5 dB, compared to 3% of the samples exhibiting greater than 15 dB of fading without compensation. The new technique is a simple and complete solution for PMD-induced RF power fading, independent of the DGD of the optical fiber link or the subcarrier frequency. It can expand to multi-channel SCM operation when the total signal bandwidth of subcarrier frequencies does not exceed a specified limit.

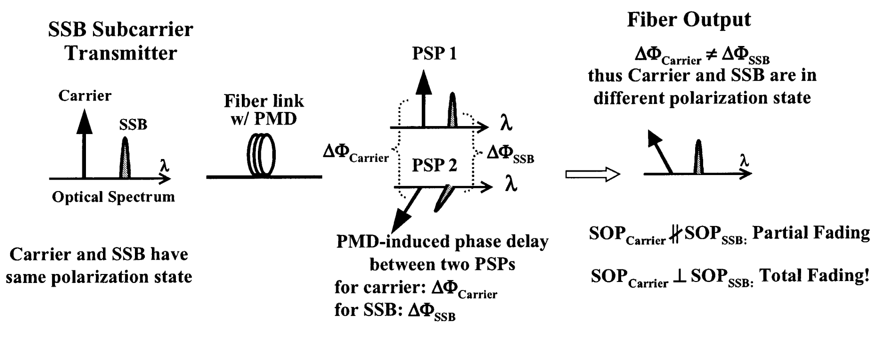
2. Concept and experiment setup

Figure 1 shows the concept for the explanation of RF power fading induced by PMD in SSB SCM systems. At the transmitter, the optical carrier and SSB have the same polarization state. After propagating through the optical fiber link, PMD induces a phase delay between two PSPs for both the optical carrier ($\Delta\Phi_{Carrier}$) and the SSB ($\Delta\Phi_{SSB}$). In general, $\Delta\Phi_{Carrier}$ is not equal to $\Delta\Phi_{SSB}$, so the optical carrier and SSB are in different polarization states at the output of the fiber, which causes RF power fading after the detection. In particular, if the polarization state of optical carrier is orthogonal to that of the SSB, the RF power will be completely faded. If the polarization states can be realigned such that they are the same for both the optical carrier and the SSB, the PMD-induced RF power fading can be completely removed.

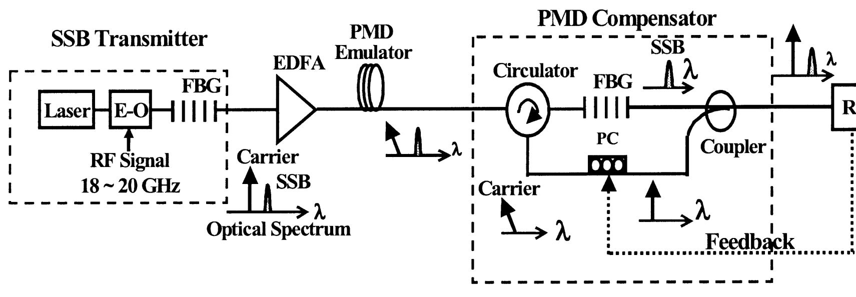
Figure 2 shows the experimental setup. We first generate an 18 ~ 20 GHz double sideband signal by externally modulating the 1550 nm optical carrier. A SSB signal is obtained by using a fiber Bragg grating (FBG) to filter out the lower sideband. After propagation through a PMD emulator, the optical carrier and SSB are separated by another FBG. The FBG has a reflection of 99.7% for the optical carrier at the wavelength of 1550 nm, with a bandwidth of 0.1 nm. The reflected optical carrier passes through a polarization controller (PC) so that its polarization state can be aligned to be the same as the SSB. Then the optical carrier and SSB are recombined at the receiver. By adjusting the PC to maximize the received RF power, the faded RF signal can be completely recovered after the detection.

3. Results and discussion

For the PMD emulator in the experimental setup, firstly we used a PC and a polarization-maintaining (PM) fiber with varying lengths to simulate the first-order PMD (DGD). The power splitting ratio was 0.5. Figure 3 shows the measured RF power fading compared to the theoretical value, and the compensated result. We can see that the RF power fading is reduced to less than 1 dB after compensation.



WQ5 **Fig. 1.** Explanation of PMD-induced RF power fading in a SSB SCM system in optical domain.



WQ5 **Fig. 2.** Experimental setup.