Pulse Restoration by Filtering of Self-Phase Modulation Broadened Optical Spectrum

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***Abstract*—Restoration of distorted optical pulses is achieved using nonlinear fiber self-phase spectral broadening and subsequent optical band-pass filtering of a single sideband. Using this technique, the output pulsewidth is shown to remain constant for input pulse-widths between 9–20 ps. A detailed investigation of the signal-to-noise ratio shows that best performance is obtained by operating in normal fiber dispersion regime. This technique is also applied to restore 40 Gb/s RZ-data suffering distortion from polarization mode dispersion. The high-bandwidth fiber nonlinearity shows promise to scale to higher bit rate pulse distortion correction.**

***Index Terms*—Dispersion compensation, fiber nonlinearities, optical signal processing, polarization mode dispersion, self-phase modulation.**

I. INTRODUCTION

OPTICAL communication systems that use the return to zero (RZ) data format and operate at 40 Gb/s and beyond will require new techniques to combat transmission effects that lead to pulse broadening distortion like polarization mode dispersion (PMD) [1] and higher order chromatic dispersion [2]. Techniques exist to correct for PMD [3] and are based on two basic approaches to compensate birefringence in the transmission fiber (i) with a birefringence compensating element at the fiber output [4] or (ii) with a pre-compensating controller at the fiber input that sets the polarization state for minimum output distortion [5]. The main problem with these methods is that PMD in a transmission fiber varies over time and, thus, they rely on instantaneous information about the actual PMD value as well as orientation of the principal states of polarization (PSP).

In this paper, pulse restoration using self-phase modulation (SPM) in a dispersion-shifted fiber with subsequent optical band-pass filtering is demonstrated. The advantage with this approach is that, to a certain degree, pulse distortion can be restored using optical nonlinearities and thus no measured information about actual PMD or PSP is required. This technique has previously been demonstrated to improve the extinction ratio of RZ-data [6], which also predicts that the output pulsewidth should be independent of the input pulsewidth. The basic idea is to substantially broaden the spectrum using SPM, and subsequently slice the spectrum with an optical band-pass filter. This filter determines the output pulse-width in the same manner as with a super-continuum source [7]. The filter has to be slightly offset from the original center wavelength to select one of the two generated side bands. The long and short wavelength side bands are originated from the leading and trailing edge of the input pulse, respectively, which allows a shorter pulse at the output than at the input. Thus, the spectral broadening depends on the slopes of the input pulse rather than the actual input pulsewidth. This feature is especially useful to combat pulse splitting effects like PMD, where at least in the case of moderate first order PMD the pulse slopes are not distorted. In principle the output pulsewidth should be independent of the input pulsewidth as long as the SPM broadened spectrum is broad enough to give a linear phase of the spectrum within the bandwidth of the filter. The concept has many similarities with the generation of short pulses using super continuum in a fiber, but since much lower optical input power is used, ideally only the SPM effect in the fiber should contribute to the spectral broadening. In the case of signal degradation due to PMD, the effective pulsewidth will vary over time at the output of the system. This is due to variation in the polarization state of the signal relative to the principal states of polarization (PSP) in the system, e.g., due to mechanical disturbances, as well as variation in the total differential group delay (DGD). In addition, the PSPs of the system will vary over time [8], [9]. Here, a pulsewidth restorer is demonstrated to restore 40 Gb/s data that suffer from pulse broadening due to PMD. Another important issue is the signal-to-noise ratio (SNR) in the output signal. Slicing of a broadened optical spectrum may result in a severe degradation of the SNR if only a very small noise component is present at the input. The SNR issue is discussed in detail and measured versus input power in both anomalous and normal-dispersion regime. Spectral slicing can also be utilized in a cross-phase modulation (XPM) broadened spectrum to achieve, e.g., wavelength conversion [10], and the basic results discussed in this paper is valid also when the spectrum is broadened by XPM.

II. PULSE WIDTH RESTORATION

To demonstrate the concept of pulsewidth restoration an experimental set-up as shown in Fig. 1 was used. Pulses at 10 GHz from an actively mode-locked fiber ring laser with variable pulsewidth at a wavelength of 1541 nm was amplified to an average power of +16 dBm before entering a 5-km dispersion shifted fiber (DSF) with a zero dispersion wavelength at 1543 nm. At the output of the DSF, an optical band-pass filter (BPF) with either 0.2-nm or 0.7-nm band width was used

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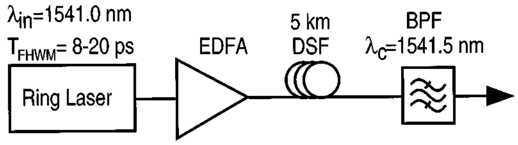

Fig. 1. Experimental setup for pulse restoration.

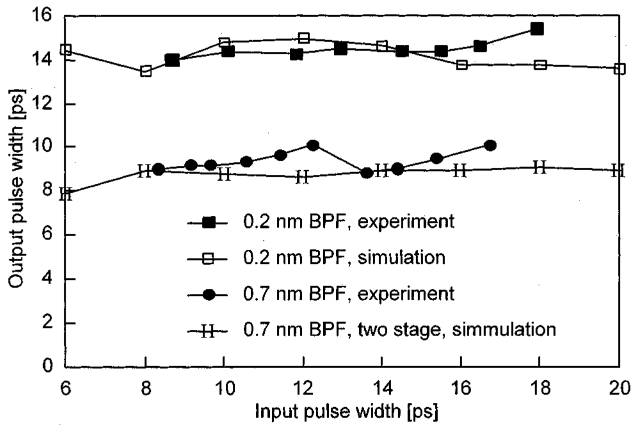

Fig. 2. Experimental and simulated results of pulsewidth restoration.

to slice the SPM broadened spectrum. The center frequency of the band-pass filter was 1541.5 nm and the output pulse characteristics were measured with a 40-GHz photodetector and a 50-GHz sampling oscilloscope. The results clearly show that the pulse-width can be equalized within a relatively large input range, which should be sufficient for combating PMD or higher order dispersion. Fig. 2 shows the output pulsewidth versus input pulsewidth for the two different filter bandwidths. The optical average input power to the fiber was kept constant, +16 dBm, due to saturation of the EDFA. In the case of a 0.2-nm BPF, trace a, the output pulsewidth is almost constant at 14.5 ps for input pulsed widths between 9–16 ps. In the case of a 0.7-nm BPF, trace b, the output pulsewidths varies between 9–10 ps for input pulsewidths from 8 ps to 17 ps. The small jump around an input pulsewidth of 13 ps is probably due to a higher intensity derivative of the SPM broadened spectrum that moves in to the transmission window of the BPF. The system in Fig. 1 was also simulated using a commercial transmission simulator software. The (G) in Fig. 2 show simulated output pulsewidths using a 0.2-nm Lorentzian shaped band-pass filter. As shown in Fig. 2, excellent agreement with the experiment was found. It is important to note that the even though the average power out of the EDFA is constant, the peak power will change according to the input pulsewidth and, thus, less SPM broadening will occur for broader pulses. However, as long as the spectrum is broad enough, the output pulsewidth will remain constant. For broader input pulses, the pulsewidth increases but the output power also becomes lower and the quality of the output pulse gets worse since the efficiency of SPM gets lower, resulting in insufficient spectral broadening. Anyway, the results clearly show that the pulsewidth can be equalized within a relatively large input range, which should be sufficient for most applications, like combating PMD or higher order dispersion. One disadvantage with the scheme in Fig. 1 is that a small wavelength shift between input and output signal is inevitable. One solution to that problem could be to make a two-stage device where SPM in a subsequent DSF once again generates a broadened spectrum. A second BPF can then be positioned at the original wavelength, giving pulsewidth restoration without wavelength translation. Trace (c) in Fig. 2 shows simulated results for such a two-stage pulsewidth restoration device with a 0.7-nm band-pass filter. The output pulsewidth is now constant 9 ps for all input pulsewidths from 8 to 20 ps. Simulations also show that the output pulsewidth is more constant with variation in input pulsewidth from a two stage device compared to a single-stage device.

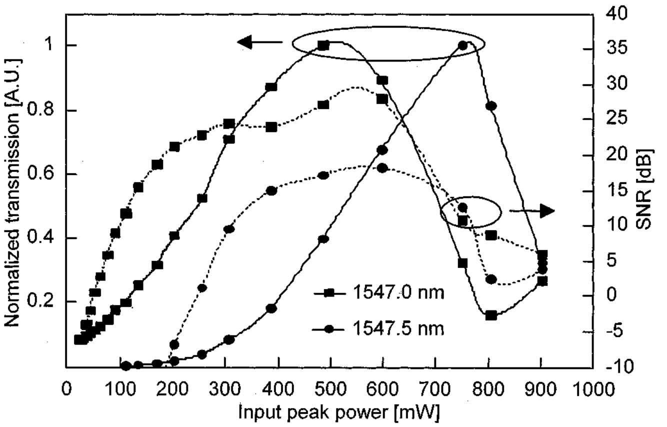

Fig. 3. Transmission and SNR versus input peak power in the anomalous dispersion regime.

III. SNR IN SLICED SPECTRUM

Under ideal circumstances, slicing of a SPM broadened spectrum should give a clean high-quality pulse, where the pulsewidth and pulse shape are determined by the filter function of the filter used. However, when operating in anomalous dispersion regime in the fiber, the filtered pulses often become noisy if the input pulses are not extremely stable in amplitude and the SNR is very high. This is due to unstable excitation of random higher order solitons either due to amplitude fluctuations in the input pulse itself or due to beating between the pulse and optical noise, e.g., from an erbium-doped fiber amplifier (EDFA). This phenomenon has been shown to become a severe limitation in the generation of super continuum [11], [12] where the input peak power has to be extremely high compared to what is required for generation of a fundamental soliton. Here, we show that this effect also has severe noise implications even at the much lower input power required for moderate SPM broadening of the spectrum. In this case, the growth of noise is characterized by measuring the SNR versus input power for a sliced SPM broadened spectrum. Random generation of higher order solitons, when pumping the fiber in the anomalous dispersion regime, may also impair other all optical fiber devices, like the nonlinear optical loop mirror and devices relying on four wave mixing.

The origin of the phenomenon is that solitons of different orders can have a very different evolution upon propagation along the fiber and in a certain point along the fiber the spectral shapes of each pulse may be different between each individual pulse in the pulse train if small noise is present at the input. If the

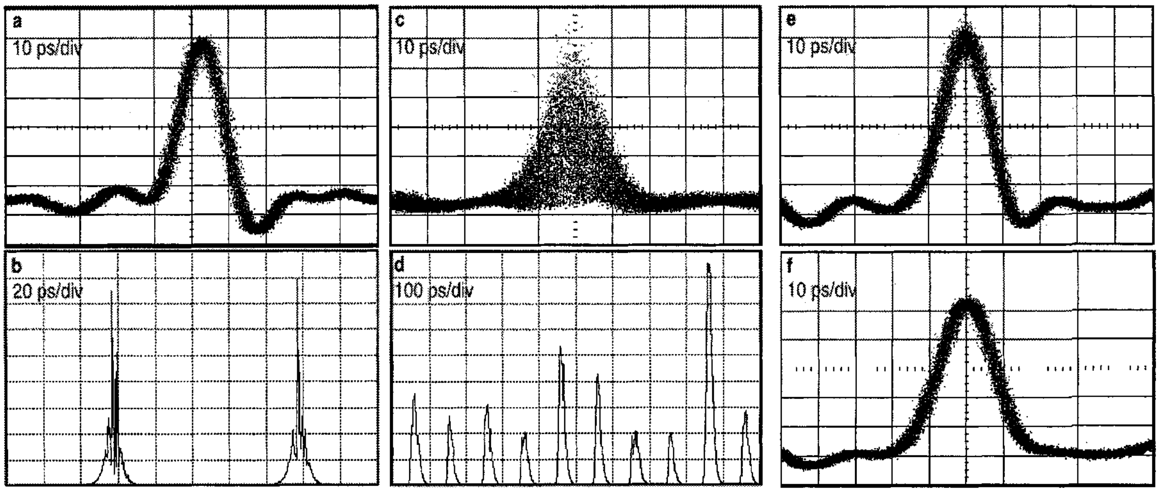

Fig. 4. Measured and simulated optical pulses. (a)–(d) Pulses in the anomalous dispersion regime. (e)–(f) Pulses in the normal dispersion regime, without (a), (b), (e) and with (c), (d), (f) a 0.2-nm filter.

band-pass filter is not positioned exactly after one or a multiple of soliton periods the random variation in the shape of the spectrum is translated into amplitude noise after filtering.

A. Experiments and Simulations

An 8-ps soliton like pulse train with a repetition rate of 10 GHz from an actively mode locked fiber ring laser was amplified in an EDFA and injected into a 5-km dispersion shifted fiber with a zero dispersion wavelength of 1543 nm. The spectrum was broadened due to SPM in the fiber, and at the output a tunable 0.2-nm band-pass grating filter was used to slice out a part of the spectrum. To estimate the SNR, the output signal was analyzed with an electrical spectrum analyzer and the noise power was integrated from 50 to 9.9 GHz and compared with the power in the fundamental 10 GHz tone. The simulations were performed using a commercial transmission simulator (OptSim) using the same components and specifications as in the experiments. Fig. 3 shows the transmission from input to output and variation in SNR when pumping the fiber in the anomalous dispersion regime at 1546.5 nm and the SNR in the input pulses was better than 25 dB. The measurements were carried out with the filter set at 1547.0 nm (B) and 1547.5 nm (J). The transmission functions have the same principal behavior, but the peak power required for maximum transmission increases as the filter is positioned away from the input center wavelength. The output SNR for low input power is low due to the low output power compared to noise from the detector and spectrum analyzer, and thus increases as the transmission goes up. At a certain power level the SNR begins to decrease due to the generation of random higher order solitons. The net effect in this region is that noise at the input signal is amplified due to modulation instability (MI) on the pulse [13], [14] and results in a random pulse evolution in both the temporal and spectral domain. When looking at the SPM pulse without the filter in the temporal domain using an oscilloscope, the pulses do not look noisy since the integrated energy within the time resolution of the oscilloscope is constant, see Fig. 4(a). Fig. 4(b) shows simulated output pulses with a high resolution, where all pulses look different even though the integrated pulse energy may still be the same. Fig. 4(c) and (d) show measured and simulated pulses, respectively, after the 0.2-nm band-pass filter. The pulses are now extremely noisy, i.e., all pulses have different amplitude due to the random energy distribution in the spectrum. Fig. 5 shows the transmission and SNR measurements when the fiber was pumped in the normal dispersion regime at 1539.5 nm and the filter positioned at 1540.0 nm and 1540.5 nm. The transmission function looks somewhat different and more input peak power is required for maximum transmission. On the other hand there is no decrease in SNR for high input powers since no solitons are generated in the normal dispersion regime and MI cannot occur. Fig. 4(e) and (f) show a measured output pulse at 1539.5 nm without filtering and sliced output pulse at 1540 nm, respectively. Here no addition of noise is observed after filtering. The aforementioned results have also direct implication on randomness of XPM of another signal [10], since the pump required for XPM always suffers SPM. However, the interplay between SPM and XPM in the presence of dispersion is complex and discussed in, e.g., [15].

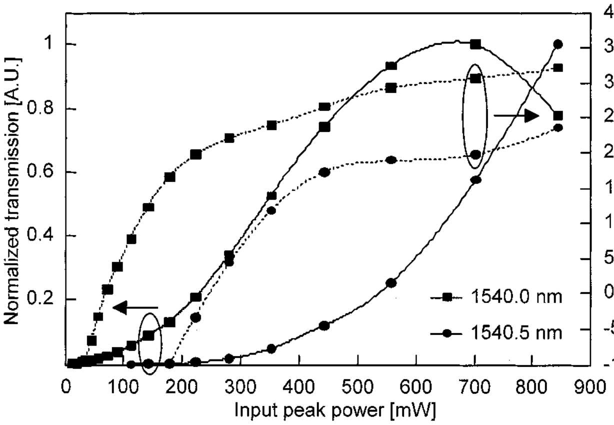

Fig. 5. Transmission and SNR versus input peak power in the normal dispersion regime.

IV. PMD RESTORATION

To demonstrate restoration from PMD distortion, an experiment as depicted in Fig. 6 was performed. 10 Gb/s data was encoded on 8-ps pulses from an actively mode-locked fiber ring laser at a wavelength of 1547 nm. The 10 Gb/s data was then

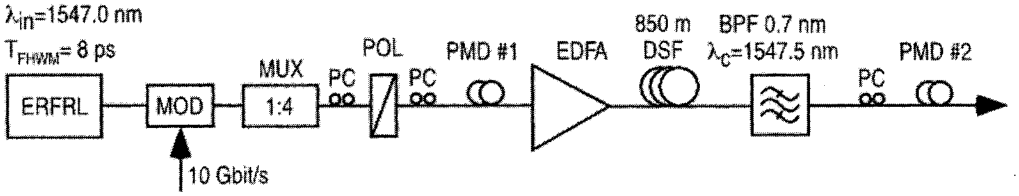

Fig. 6. Experimental setup for PMD restoration. ERFRL: Erbium-doped fiber ring laser; MOD: LiNb03 modulator; MUM passive 10–40 Gb/s multiplexer; PC: polarization controller; POL: polarizer; PMD #1: PMD emulator with 10-ps DGD; EDFA: erbium-doper fiber amplifier; DSF: dispersion shifted fiber; BPF: optical bandpass filter; PMD #2: PMD emulator with 6-ps DGD.

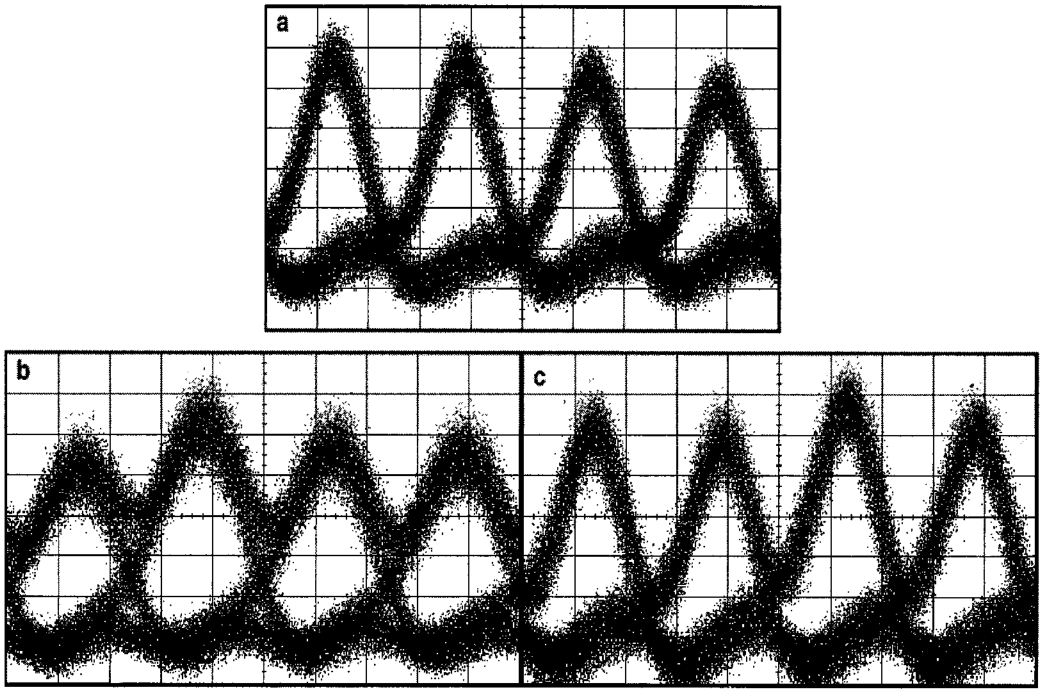

Fig. 7. (a) Input 40 Gb/s data. (b) Data after 10 ps DGD. (c) Data after pulsewidth restoration.

passively time multiplexed to 40 Gb/s using a split, delay, and interleave type of multiplexer based on 50/50 fiber couplers and variable optical delay lines. A linear polarizer was placed at the output of the multiplexer to ensure equal state of polarization of the 40 Gb/s data stream. This is important since otherwise each channel will be impaired differently by the PMD. The 40 Gb/s data was sent through a PMD emulator consisting of 12 sections of birefringent fiber spliced with random angels giving a measured differential group delay of 10 ps at 1547 nm. A polarization controller was used at the input of the PMD emulator to adjust the input data polarization state to equally excite the principal states of polarization in the emulator. In this way the PMD emulator causes maximum distortion of the data. The distorted data was then sent through a pulsewidth restorer as described in Section II. In this experiment, an EDFA with 1-W average output power was used and, thus, only 850 m of DSF was needed to achieve sufficient SPM broadening of the 40 Gb/s data. Again, a 0.7-nm optical band pass filter was used to slice the SPM broadened spectrum to restore the pulsewidth. The restored data was then send through another PMD emulator consisting of eight sections of birefringent fiber spliced with random angles, giving a differential group delay of 6 ps at 1547 nm. The receiver contained a phase-locked loop based clock recovery circuit utilizing an electro-absorption modulator to recover a 10-GHz clock from the 40 Gb/s data. This allowed stable visualization of the PMD distorted data on a sampling oscilloscope. Fig. 7(a) shows the input 40 Gb/s data, and Fig. 7(b) shows the data distorted by 10 ps DGD in the PMD emulator. The eye patterns look more open due to the broader pulses caused by the DGD, but the pulsewidth is now about 15 ps. Fig. 7(c) shows the data after restoration in the pulsewidth restorer and the pulsewidth comes down to 10 ps. Fig. 8 shows the data after the second PMD emulator. Fig. 8(a) is with and Fig. 8(b) is without the pulsewidth restorer. In the case of retransmitting the previously restored data through a second PMD emulator, the eye patterns are still clearly open, while without restoration the eye patterns are heavily distorted. However, if the data suffers too much PMD, i.e., the pulses get too broad, the pulse shape cannot be restored since the adjacent data channels will start to interfere. This interference distorts the slopes of the pulses that give rise to the spectral broadening in the SPM fiber. In the case of PMD restoration, it is important that the data does not suffer from too much PMD before being restored, but once restored it can suffer from more PMD again. The amount of allowed PMD before restoration depends then on the input pulsewidth and pulse shape to the system, as well as the bit rate.

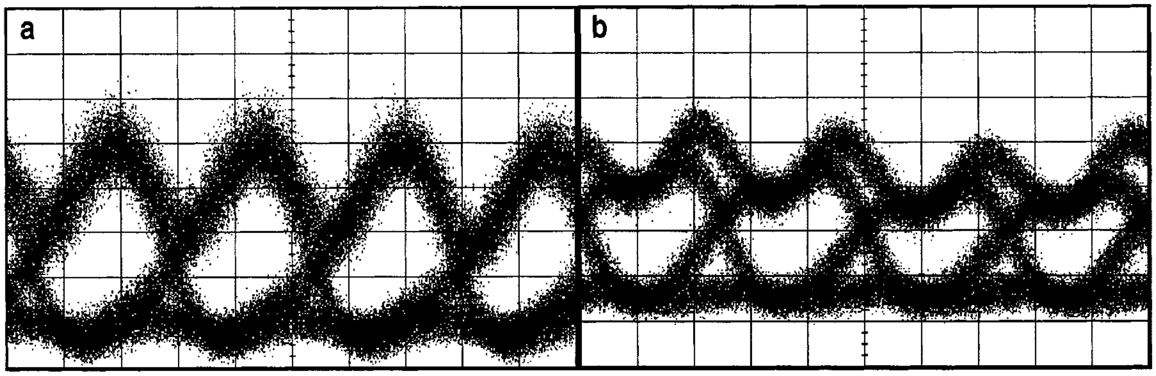

Fig. 8. 40 Gb/s data after additional 6 ps DGD, (a) with restored pulses and (b) without restoration; 10 ps/div.

V. CONCLUSION

Restoration of pulsewidth using self phase modulation in a dispersion-shifted fiber with subsequent filtering has been demonstrated. The output pulsewidth is shown to be a constant 10 ps, ±1 ps for an input pulsewidth range of 8–16 ps. The SNR of the output signal after restoration was investigated and high SNR is obtained when operating in the normal dispersion regime of the fiber, while a limitation in the allowed input power occurs in the anomalous dispersion regime due to excitation of random higher order solitons. The scheme was also applied to restore 40 Gb/s data suffering from PMD. The device could potentially be used in transmission links to restore from both PMD and remaining uncompensated chromatic dispersion, e.g., higher order dispersion which may be difficult to compensate for. An interesting extension of this scheme could be to make SPM spectral broadening an integral part of the transmission properties of a communication system and have filters placed through out the system to perform the pulse restoration.

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