Optical Dispersion Monitoring Technique Using Double Sideband Subcarriers

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***Abstract*—A technique for measuring the accumulated dispersion affecting a digital optical signal without recovering the baseband was developed and experimentally demonstrated. This technique allows measurement of the accumulated dispersion independently of the data origin and transport history. The technique employs an amplitude-modulated double-sideband subcarrier applied to the signal at the transmitter and monitored at an arbitrary point in a link or network using a novel suppressed-sideband optical-tap technique. The phase difference between the upper and lower sidebands of the subcarrier signal is measured and used to compute the dispersion. A combined coarse and fine measurement realizes high accuracy and large dynamic-range dispersion monitoring.**

***Index Terms*—Dispersion measurement, fiber dispersion, subcarrier multiplexing, optical networks, wavelength division multiplexing, WDM systems monitoring.**

I. Introduction

THE prospect of high-bandwidth transparent wavelength division multiplexed (WDM) optical networks has spurred an interest in developing new ways to monitor the channel performance and data degradation. Currently, the bit error rate (BER) and Q-factor are measured from bits interleaved within SONET frames. However, this approach requires that the signal is returned to the electronic domain and terminated by a SONET line terminating element. In an ideal transparent WDM optical network, one would like to determine the BER of a given wavelength channel without electronic termination. However, direct BER measurements are difficult as only a small percentage of optical power can be monitored without degrading the through signal. Another approach is to monitor the parameters (chromatic dispersion, polarization mode dispersion, crosstalk, jitter, extinction ratio, channel power) indicative of channel degradation directly and compute the BER or performance from these measures. It may also be desirable to characterize certain parameters of a data channel for corrective measures (such as dispersion compensation) or for network management purposes (such as downgrading a channel's bit rate).

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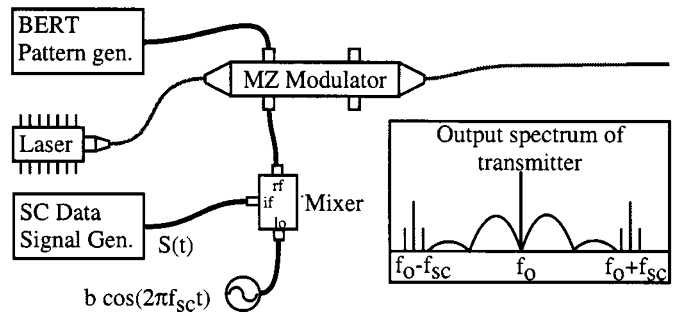

Fig. 1. Schematic diagram of transmitter.

Previously reported work on optical performance monitoring includes: power equalization of WDM channels using an optical spectrum analyzer [1] and WDM channel power monitoring using subcarrier signals and an electrical spectrum analyzer [2].

In this letter, we describe a method of monitoring the dispersion affecting a data channel without recovering the baseband data. Results of a proof of concept experiment are presented. It is important to note that our method differs from techniques [3] that characterize the fiber or fiber span. Our method measures the accumulated dispersion experienced by the optical signal independent of the signals path and thus has application to optical networks where different wavelengths can traverse different paths, each potentially dynamic and unknown at the monitoring point.

II. Principle of Operation

Our technique involves the use of a modulated subcarrier signal added to the baseband data at the transmitter. A schematic diagram of the transmitter is shown in Fig. 1. The transmitter architecture is the same as was described in [4] where it was used to encode labels on data packets. The spectrum of the transmitter output (depicted in the inset to Fig. 1) shows the double sideband nature of the subcarrier signal. When this signal is propagated through dispersive fiber, the dispersion induces a relative time delay between the subcarrier sidebands given by [5]

$$\Delta t = f_{SC} \frac{\lambda^2}{C} DL \tag{1}$$

where λ is the optical carrier wavelength, c is the vacuum light speed, f_{SC} is the subcarrier frequency, D is the dispersion coefficient, and L the length. This effect is well known and is responsible for the fading experienced in double sideband subcarrier signals when direct detection is employed. By measuring

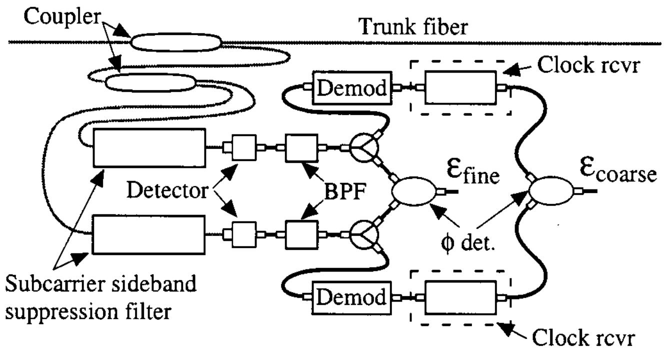

Fig. 2. Schematic diagram of dispersion monitor. BPF are electrical bandpass filters. $\varepsilon_{\text{coarse}}$ and $\varepsilon_{\text{fine}}$ are outputs indicating the amount of dispersion affecting the optical signal.

the relative phase delay between the sidebands, it is possible to determine the amount of dispersion (DL product) the baseband signal has experienced.

The tap architecture we propose for monitoring the dispersion experienced by the optical signal combines these two techniques making possible the measurement of a wide range of dispersion with high resolution. A schematic diagram of the tap architecture is shown in Fig. 2. Referring to the figure, a portion of the optical signal is removed from the trunk fiber, divided into two, and transmitted through optical filters that suppress the upper and lower sidebands, respectively. Following the filtering, both signals are detected and the baseband data is removed using electrical bandpass filters. Each of these signals are then further divided with one output providing an input to a phase detector and the other output being directed to an amplitude demodulator. The phase detector produces a signal proportional to the phase difference between the subcarrier signals. This provides a fine measurement of dispersion as explained earlier, according to (1). The outputs of the amplitude demodulators are directed to a second phase detector that provides a coarse measurement of dispersion. The coarse measurement may be used to resolve phase ambiguities in the fine measurement. A clock recovery step is only necessary when data is encoded on the subcarrier (i.e., packet labels as in [4]). In that case, the recovered clock is input to the second phase detector to obtain the coarse measurement.

It is clear from (1) that by choosing a subcarrier frequency that is large compared to the bit rate of the underlying data, very sensitive measurement of accumulated dispersion is possible. For example, for f_{SC} = 16.4 GHz and λ = 1560 nm, a delay of 5 ps (1/12 the period) is easily measured, leading to a DL product of 37.6 ps/nm. This corresponds to propagation through 2 km of standard fiber. Unfortunately, measurement of the subcarrier phase delay alone limits the maximum dispersion that can be measured to the period of the subcarrier signal.

It is possible to overcome this limit to measurement of high values of dispersion by measuring the delay experienced by a relatively low frequency modulation applied to the subcarrier signal. In this case, the time delay between the modulation on the upper and lower sidebands is given by [5]

$$\Delta t = 2 f_{SC} \frac{\lambda^2}{C} DL. \tag{2}$$

In this way, the range of the measurement is extended to delays comparable with the period of the modulation applied to the subcarrier signal, much longer than in the previous case. With the same values of the previous example and a SC modulation frequency of 410 MHz, the maximum DL product that can be resolved is 9167 ps/nm. Of course, the accuracy is lower.

III. Experiment

In this section, we report the results of a proof of principle experiment. It is important to note that certain aspects of our set-up were not optimal, particularly the optical filters. Nevertheless we demonstrate that measuring a wide range of DL product with accuracy is possible using this technique.

A. System Setup

The experimental setup follows that depicted in Figs. 1 and 2, with several noteworthy exceptions. The transmitter employed an 18-GHz $LiNbO_3$ Mach–Zender modulator used to simultaneously encode baseband 2.5-Gb/s data and a 16.4-GHz subcarrier on a 1560-nm wavelength DFB laser. The subcarrier was amplitude modulated with a dc offset 410-MHz sinusoidal tone. The sinusoidal format was chosen for practical proposes, but digital data can be used as well.

The optical signal was propagated through varying lengths of step-index single-mode fiber to simulate different DL products. At the end of the link, the signal was optically amplified and split into two. On one arm, the baseband data were detected, while the other was input to the dispersion monitor. The dispersion monitor follows the design illustrated in Fig. 2, with the exception that following the electrical bandpass filters the signals were amplified and input to a sampling oscilloscope. The waveforms were acquired with the oscilloscope and transferred to a computer where the phase detection and demodulation functions were performed in software. The most critical elements in the dispersion monitor are the optical filters that perform the sideband rejection. In our experiment these were tunable bandpass filters (FWHM equal to 0.2 nm) adjusted to provide maximum rejection of the unwanted sideband while producing minimum attenuation of the desired sideband. Unfortunately, one of these filters performed much worse than the other. The upper filter provided 24.3 dB of rejection but the lower filter provided only 14.8 dB of rejection.

B. Results

Fig. 3 shows the results of the demonstration of the dispersion monitor. In Fig. 3(a), the coarse and fine delays are plotted as a function of fiber length. Also plotted in the figure (the solid line) is the theoretical curve given by (1). The coarse delay has been divided in two [(1) and (2) differ by a factor of two] so that both the coarse and the fine measurements can be compared to the same theoretical curve. The dashed lines are upper and lower bounds for the coarse measurement obtained by adding (subtracting) one half of the subcarrier period to (from) the theoretical curve. Provided the coarse delay measurements fall within these bounds, it is possible to correctly determine the proper order of the fine phase measurements. Fig. 3(b) shows the fine phase data after it has been unwrapped. Evident in the figure

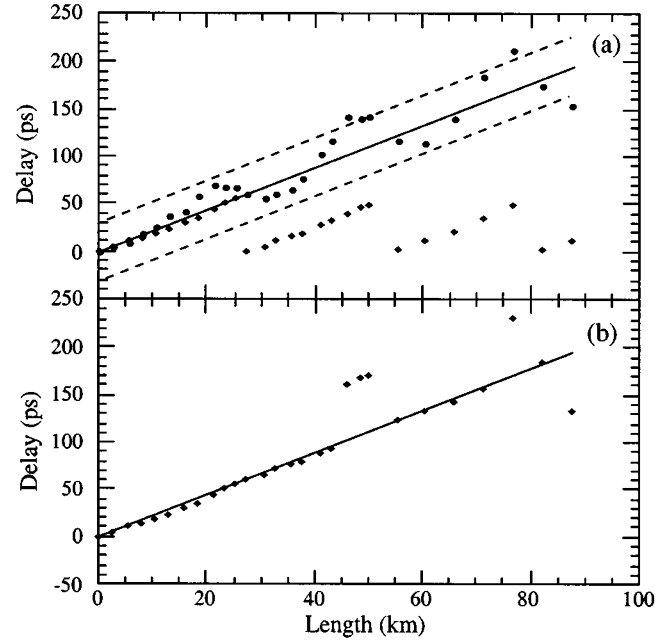

Fig. 3. Results of a proof of principle experiment. (a) Measured coarse delay divided by two (·) and fine delay (⋄) plotted as a function of fiber length. Solid line is the theoretical delay given by (1). Dashed lines are upper and lower bounds for the coarse measurements. (b) Fine delay versus fiber length after it has been unwrapped and the ambiguities resolved.

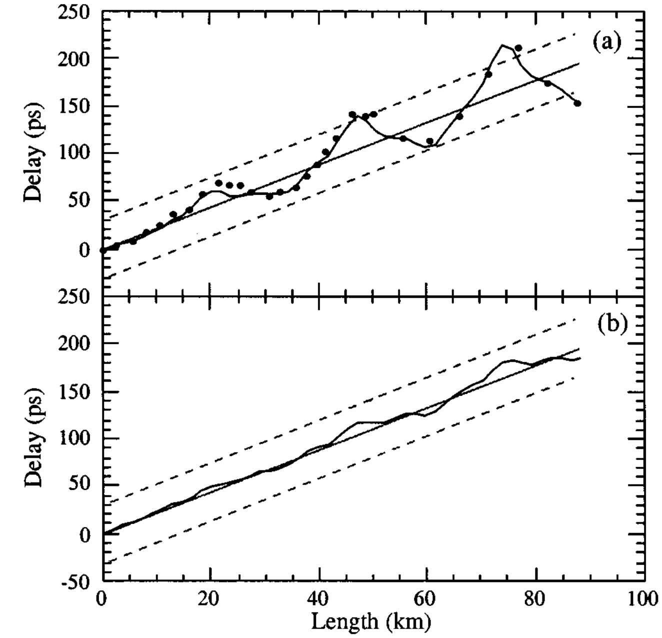

Fig. 4. Results of simulation and experiment. (a) Measured coarse delay (·) compared to the results of a simulation (solid line). (b) Simulation showing predicted coarse phase measurement with optical filters providing 30 dB of sideband rejection.

are some errors that resulted from coarse phase measurements that exceeded the limits shown in Fig. 3(a). We have determined through simulation of the system that these errors are a direct result of the poor sideband extinction obtained from the sideband rejection filter. Fig. 4 shows the results of our simulation. In Fig. 4(a), the measured results are shown as points and the solid line is the output of the simulator. Excellent agreement between simulation and experiment is obtained. Fig. 4(b) shows the coarse delay as a function of length that would be obtained (according to our simulation) with filters that provide 30 dB of sideband suppression. Results from the simulator show that using the coarse measurement it is possible to resolve the ambiguities in the fine measurements to a time delay equal to the full period of the modulation applied to the subcarrier. This delay is equivalent to that produced by about 500 km of standard fiber or an equivalent DL product of 9167 ps/nm.

The use of the subcarrier signal not only adds complexity to the transmitter, but also produces some eye closure in the baseband data. In order to quantify the penalty introduced by the subcarrier modulation, we made BER measurements (2.5 Gb/s and $2^{23} - 1$ of PRBS) as a function of power at the output of the transmitter both with and without the subcarrier signal applied. We found that the subcarrier signal introduced a penalty of 0.5 dB. No error floor was observed.

IV. Conclusion

We report a technique for measuring the dispersion affecting an optical signal without recovering the baseband data. The accumulated dispersion affecting the signal is monitored using a suppressed sideband tap architecture. The technique incorporates both a coarse and a fine measurement providing high accuracy and large dynamic range. The concept was verified experimentally. As a result of the poor extinction of one of the optical filters, the dynamic range was limited to approximately two subcarrier periods. Results from a software simulator show that with improved optical filtering the full dynamic range of the method may be obtained.

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