UCRL-JC-120809
PREPRINT
CONF-9510189--7

Dispersion Reduction Technique Using Subcarrier Multiplexing

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This paper was prepared for submittal to the
All-Optical Communications Systems: Architecture, Control, and Network Issues:
SPIE Photonics East'95 Symposium
Philadelphia, PA
October 22-26, 1995

October 18, 1995

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Dispersion-reduction technique using subcarrier multiplexing

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ABSTRACT

We have developed a novel dispersion-reduction technique using subcarrier multiplexing (SCM) which permits the transmission of multiple 2.5 Gbit/s data channels over hundreds of kilometers of conventional fiber-optic cable with negligible dispersion. Using a lithium niobate external modulator having a modulation bandwidth of 20 GHz, we are able to multiplex several high-speed data channels at a single wavelength. At the receiving end, we demultiplex the data and detect each channel using a 2-GHz bandwidth optical detector. All of the hardware in our system consists of off-the-shelf components and can be integrated to reduce the overall cost. We demonstrated our dispersion-reduction technique in a recent field trial by transmitting two 2.5 Gbit/s data channels over 90 km of commercially-installed single-mode fiber, followed by 210 km of spooled fiber. For comparison, we substituted the 300 km of fiber with equivalent optical attenuation. We also ran computer simulations to evaluate link behavior. Technical details and field trial results will be presented.

Keywords: optical communication, subcarrier multiplexing, optical dispersion, dispersion compensation

1. INTRODUCTION

Fiber-optic networks demand transmission methods that offer flexibility and the efficient exploitation of bandwidth of existing network assets, such as existing conventional single-mode fiber. Wavelength-division multiplexing (WDM) has been successfully used to transmit multiple optical carriers on a single fiber. Subcarrier multiplexing (SCM) is one of the few techniques that can accommodate the multi-format array of transmission protocols and modulation formats expected to be carried on future networks. SCM can be combined with WDM to greatly increase the transmission capacity of a single fiber.

One challenge to the implementation of SCM has been the limitation on transmission distance. Normally, operation with optical carrier wavelengths of 1550 nm permits the use of erbium-doped fiber amplifiers (EDFAs) to overcome transmission loss, but the dispersion-limited maximum transmission distance of an SCM system is dependent on its total modulation bandwidth.

Another traditional drawback to SCM has been the complexity of demodulation schemes. Hill and Olshansky demonstrated SCM using coherent detection, but this technique is too impractical to use in a production telecommunications environment, and downconversion of microwave subcarriers requires phase-matching to the transmitter.[1]

Although numerous experimental high-speed SCM systems have been demonstrated, the technology has not been embraced by the telecommunications industry. Ordinary single-mode fibers have been installed all over the world, but conventional long-haul fiber systems have thus far relied on dispersion-shifted fiber in answer to the dispersion problem that accompanies wavelengths of 1550 nm.[2] Greenhalgh, et al., demonstrated an optical pre-filtering technique for subcarrier demultiplexing in a low bandwidth SCM link but did not explain how it could be used to reduce the effects of chromatic dispersion.[3]

2. THEORY OF OPERATION

Our SCM system simultaneously reduces the problems of receiver complexity and dispersion penalty without requiring the use of an expensive high-bandwidth optical detector. We offer a novel approach that results in dispersion reduction and direct detection at the receiver. Using microwave mixers and a lithium niobate external modulator, sidebands are produced a few gigahertz apart on the principal laser optical carrier. Digital data streams are independently impressed upon these sidebands for transmission over ordinary single-mode fiber.

A conceptual block diagram of our SCM system is shown in Figure 1. Independent high-speed data streams are upconverted to microwave frequencies. These subcarriers are separately amplified, and then combined using a microwave power combiner.

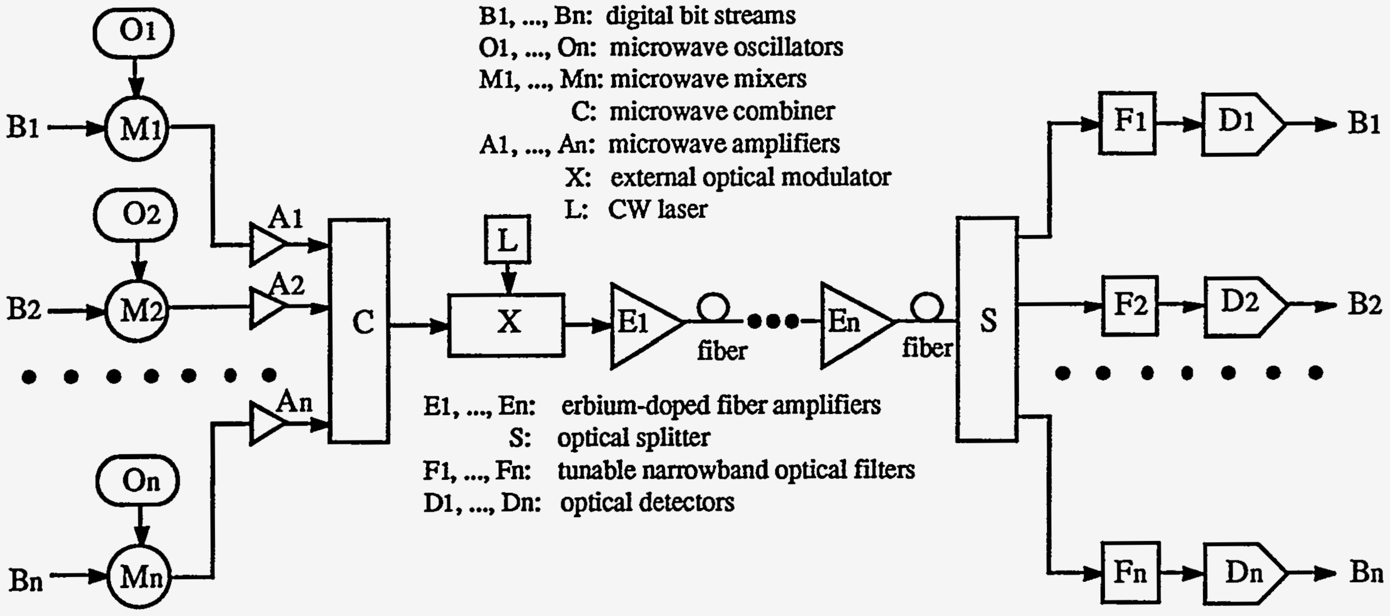

Figure 1. Conceptual Block Diagram

A diode-pumped solid-state 1550-nm laser carrier is externally modulated by the microwave subcarriers using an external modulator. Prior to long-distance transmission over ordinary single-mode fiber, the optical subcarriers are amplified using an erbium-doped fiber amplifier (EDFA). The optical signal may then traverse multiple EDFAs to compensate for fiber losses prior to detection. At the receiving end, the optical signal is split into multiple paths. The desired subcarrier channel is optically preselected using a narrowband optical filter, such as a fiber Fabry-Perot (FFP) filter. This filtering process is illustrated in Figure 2a. The ideal filtered optical spectrum is shown in Figure 2b. An optical detector converts the selected optical signal into a baseband electrical data stream (Figure 2c).

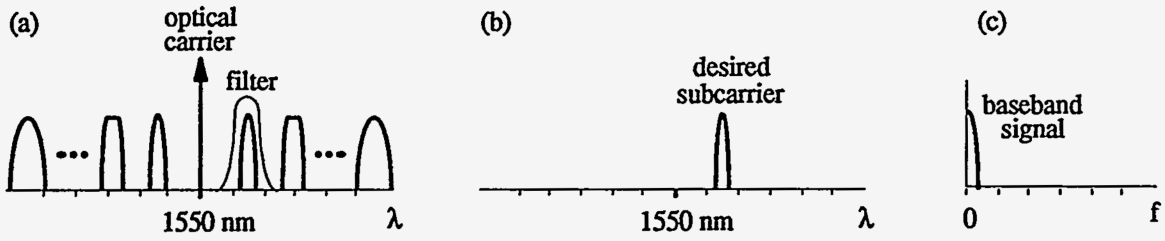

Figure 2. Optical spectrum: (a) at FFP filter, (b) after FFP filter, and (c) Frequency spectrum after optical detector

3. DISPERSION MODELING

Prior to implementation of this concept, we developed some optical network models using National Instruments' LabVIEW, a high-level object-oriented software package. These models enable us to analyze the fiber dispersion problem and to evaluate the effectiveness of the SCM technique at reducing dispersion.

Figure 3 shows the modeled frequency spectrum of an SCM system with two 2.5 Gbit/s channels, referenced to the optical carrier. Using a dispersion constant of 16 ps/nm•km, the baseband frequency response of 6 km of fiber is calculated[4] and plotted in the same figure. If the traditional subcarrier demultiplexing technique (microwave downcoversion) is used, an 18-GHz bandwidth optical detector will be required to downcovert both subcarriers. It is clear from Figure 3 that chromatic dispersion limits the fiber length of such a system to 6 km.

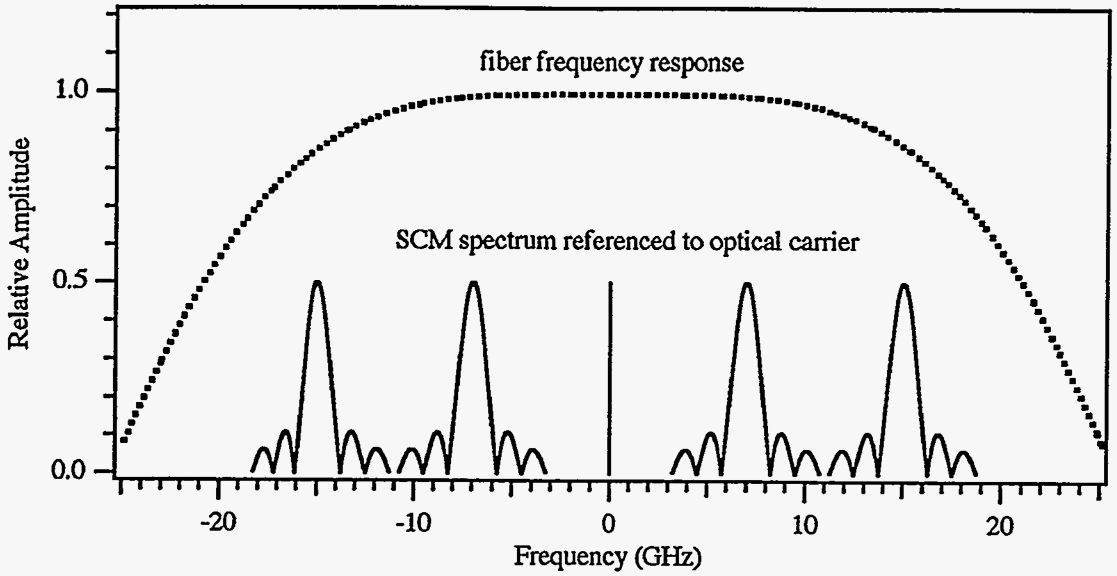

Figure 3. Frequency response of 6 km of fiber and spectrum of 2-channel SCM prior to optical detection

In contrast, if the optical pre-filtering technique shown in Figure 1 is used, the optical detector bandwidth requirement is reduced to the bandwidth of one subcarrier. The frequency spectrum of a 2.5 Gbit/s subcarrier is plotted in Figure 4. Here, the subcarrier spectrum is referenced to the subcarrier wavelength itself. The baseband frequency response of 640 km of fiber is calculated and plotted in the same figure. As the fiber length is increased above 640 km, chromatic dispersion will begin to distort the optically pre-filtered 2.5 Gbit/s data. The dispersion limit for other bit rates is given by

$$B^2L = 4000\ (\mathrm{Gbit/s})^2 \cdot \mathrm{km},$$

where B is the bit rate in Gbit/s and L is the fiber length in kilometers.[5]

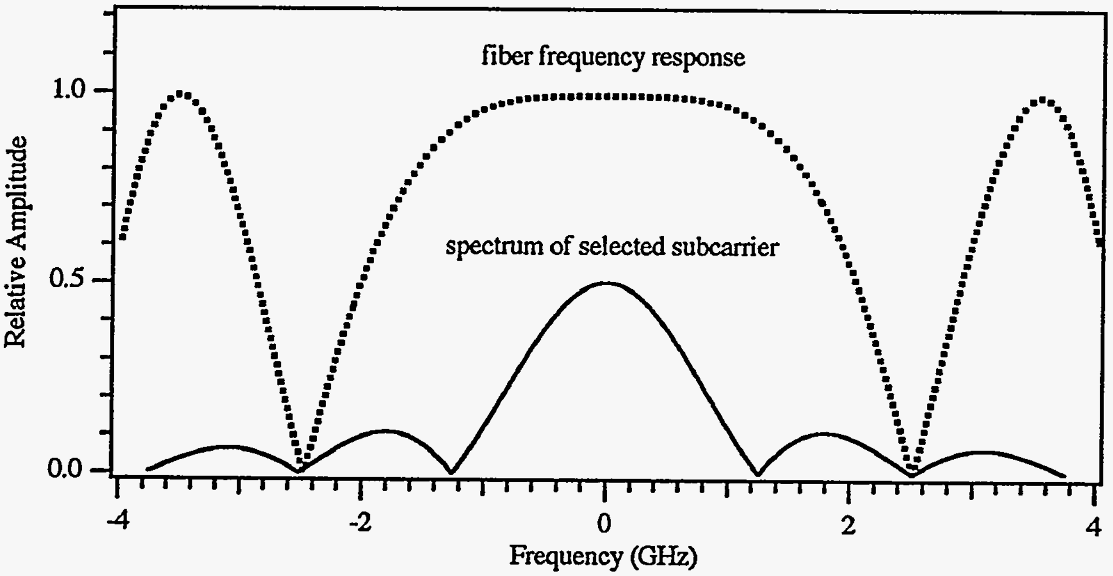

Figure 4. Frequency response of 640 km of fiber and spectrum of an SCM channel after FFP filter

4. SYSTEM DESCRIPTION

In a recent experiment with our prototype SCM system, we transmitted two 2.5 Gbit/s data channels over ordinary single-mode fiber from our laboratory in Livermore to Pacific Bell's central office in San Ramon, 45 km away. The fiber was looped back to our laboratory, where we added another 210 km of spooled fiber to form a 300 km link. A block diagram of our experimental setup is shown in Figure 5.

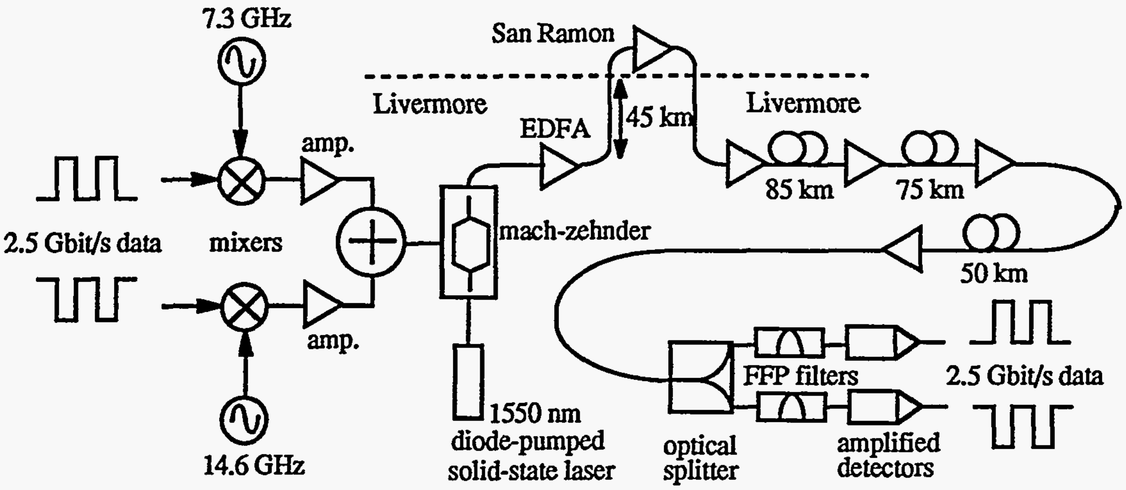

Figure 5. Block diagram of 300 km experiment

For this series of tests, an uncorrelated pair of 2.5 Gbit/s data streams were upconverted to 7.3 and 14.6 GHz. These microwave subcarriers were impressed onto a 1550 nm lightwave carrier using an 18-GHz Mach-Zehnder interferometric modulator. To suppress the main optical carrier, the modulator was maintained at null bias. The SCM lightwave signal was amplified using an EDFA to overcome losses in the fiber to San Ramon. Each additional EDFA in the link was positioned to compensate for approximately 20 dB of optical loss. At the output of the post-amplifier, the desired subcarrier was optically pre-selected using a fiber Fabry-Perot (FFP) filter having a bandwidth of 4 GHz and a finesse of 125. A 2-GHz bandwidth optical detector was used to convert the selected optical subcarrier back into a baseband electrical 2.5 Gbit/s data stream.

5. RESULTS

To demonstrate the dispersion reduction effect and to verify the accuracy of our models, the 2.5 Gbit/s repeating pattern (11001010) shown in Figure 6 was impressed upon the 7.3 GHz subcarrier and was transmitted over the full 300 km of fiber. (The 14.6 GHz subcarrier was turned off for this test.)

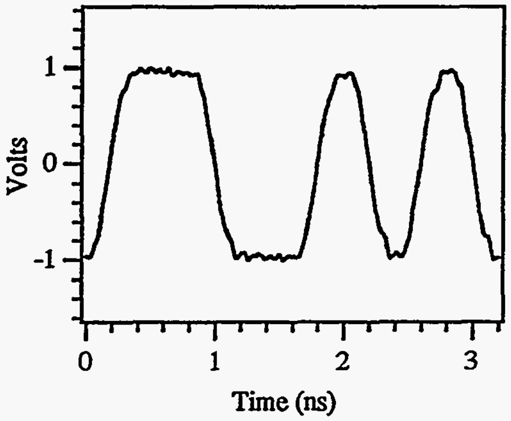

Figure 6. 2.5 Gbit/s repeating pattern at input of subcarrier channel under test

With the FFP filter bypassed, the received pattern recorded in Figure 7(a) was severely distorted due to dispersion. This same test was modeled using LabVIEW, and the result is shown in Figure 7(b) for comparison.

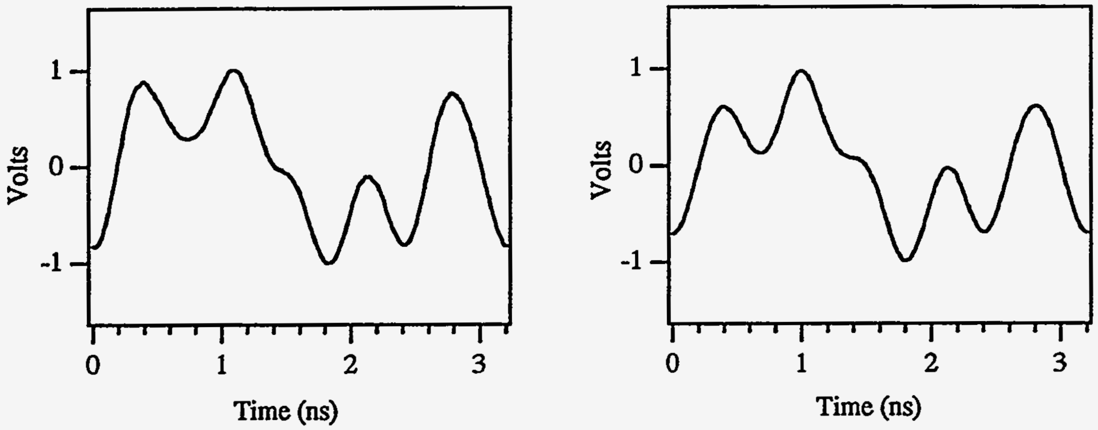

Figure 7. 2.5 Gbit/s data pattern from 7.3 GHz channel output without dispersion reduction: (a) measured, (b) modeled

In contrast, when the FFP filter was placed back in line and tuned to the 7.3 GHz subcarrier, Figure 8(a) shows that signal distortion due to chromatic dispersion was practically eliminated. Results from the computer model in Figure 8(b) are similar. The slight difference in wave shape of the measured signal is due to the transient response of system components.

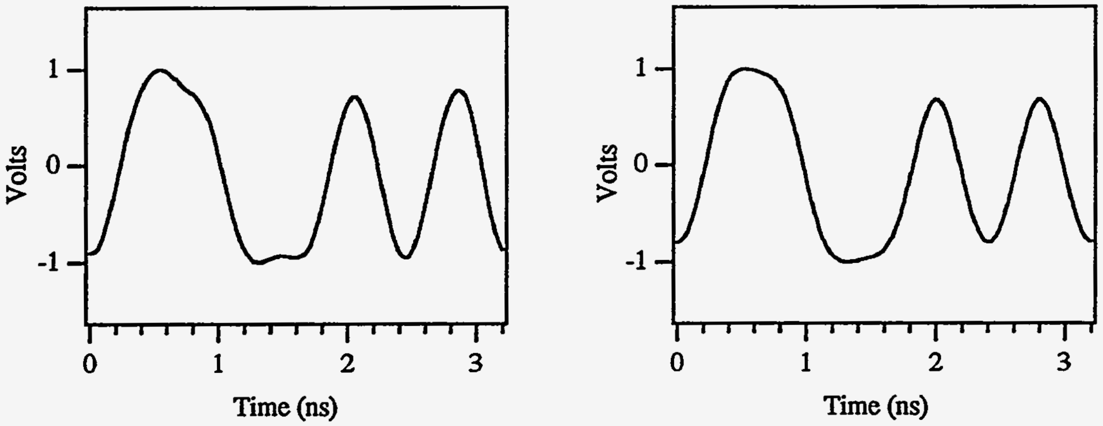

Figure 8. 2.5 Gbit/s data pattern from 7.3 GHz channel output with dispersion reduction: (a) measured, (b) modeled

Since the dispersion effect is worse at higher subcarrier frequencies, it is of interest to repeat this test on the 14.6 GHz subcarrier with the 7.3 GHz channel turned off. With the FFP filter bypassed, the output from the 14.6 GHz channel shown in Figure 9(a) looked nothing like the input in Figure 6. However, the computer simulation in Figure 9(b) shows good agreement with the measurement.

The dispersion reduction capability was restored to the system by reinserting the FFP filter and tuning it to the 14.6 GHz subcarrier. The output signal in Figure 10(a) shows the overwhelming improvement in performance. When this test was modeled, the result shown in Figure 10(b) was in agreement.

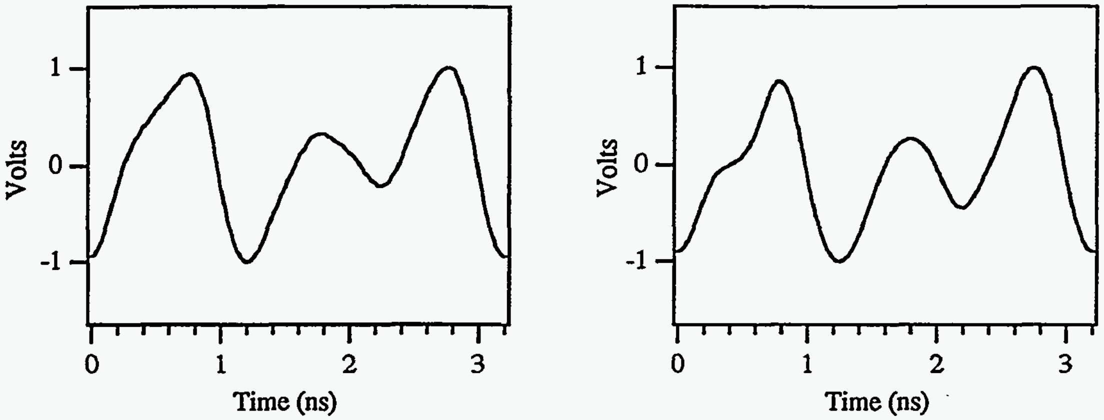

Figure 9. 2.5 Gbit/s data pattern from 14.6 GHz channel output without dispersion reduction: (a) measured, (b) modeled

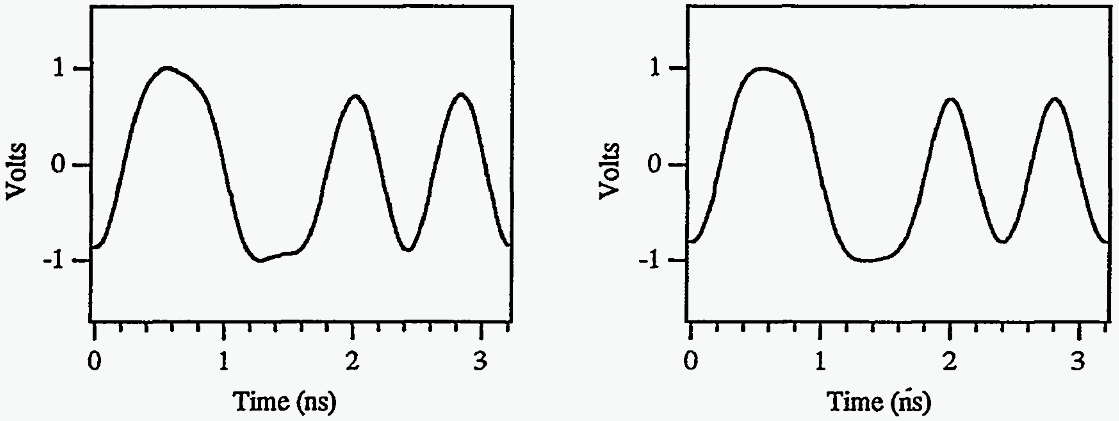

Figure 10. 2.5 Gbit/s data pattern from 14.6 GHz channel output with dispersion reduction: (a) measured, (b) modeled

Another technique for evaluating system performance involves substitution of each fiber run with an equivalent optical attenuator. By retaining all six EDFAs in the system during the attenuation test, any increase in noise or signal distortion noted in the fiber test can be directly attributed to the fiber itself. In this series of measurements, uncorrelated pseudorandom bit streams were simultaneously impressed upon the 7.3 and 14.6 GHz channels, so that each channel would experience crosstalk from the other. Eye diagram measurements were performed with an optical power level of -20 dBm at the detector. Also, bit-error rate measurements were made at various received optical power levels.

Figure 11 (a) and (b) shows a comparison of the eye diagrams that resulted from optically pre-selecting the 7.3 GHz subcarrier with 300 km of fiber and with optical attenuators, respectively. The noise level appears to be slightly lower in the measurement using attenuators. Figure 12 (a) and (b) shows the same comparison for the 14.6 GHz subcarrier. The difference in noise levels is barely perceptible in this pair of measurements

The quantitative difference in performance between a fiber-based link and an attenuator-based link can be evaluated by recording the bit-error rate (BER) as the received optical power is varied. It should be noted that the avalanche photodiode receiver used in this experiment has a sensitivity rating of -27 dBm for a BER of 10^{-10}. The results, presented in Figure 13, confirm that there is a slight noise penalty when fiber is used instead of attenuators. In addition, the optical detector requires approximately 1 dB more signal at 14.6 GHz than it does at 7.3 GHz to achieve the same bit-error rate. The same conclusion could be drawn from Figures 11 and 12 by noting that the 14.6 GHz eye diagrams are somewhat noisier than the 7.3 GHz eye diagrams. This performance difference between subcarriers can be attributed to the transient response of the microwave components.

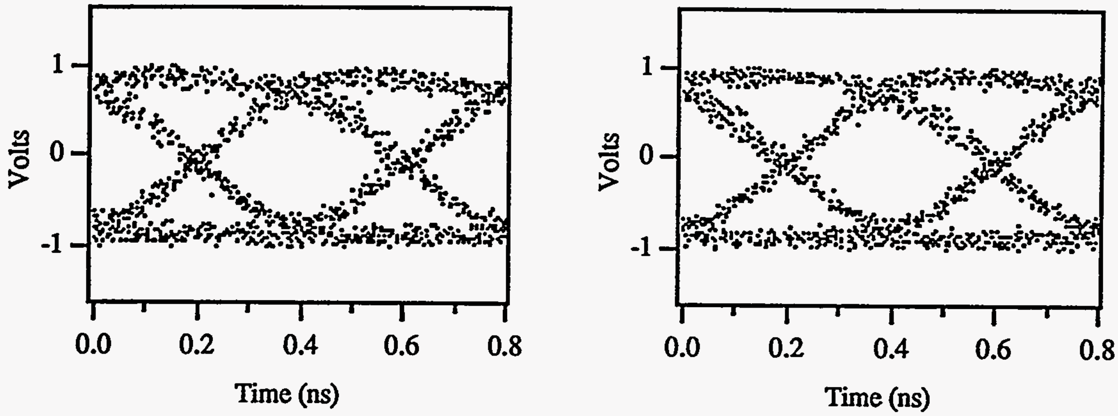

Figure 11. Eye diagrams from output of 7.3 GHz channel: (a) with 300 km of fiber, (b) with optical attenuators

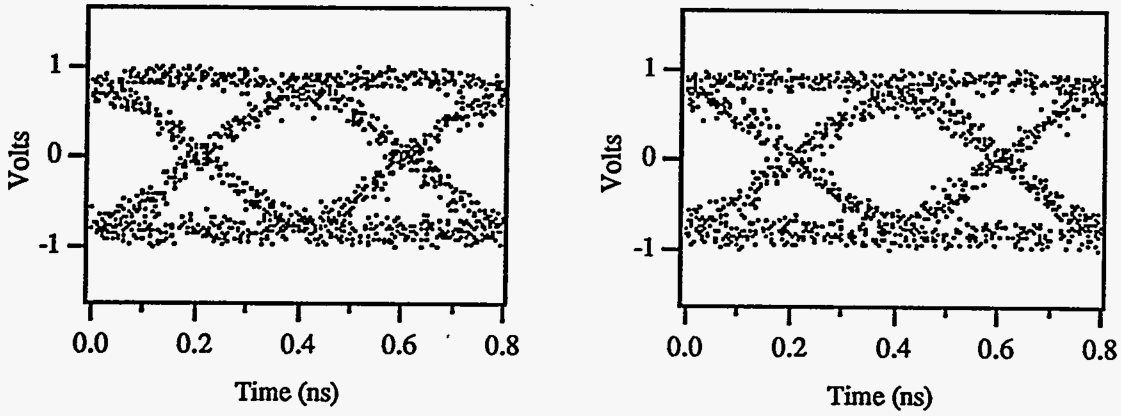

Figure 12. Eye diagrams from output of 14.6 GHz channel: (a) with 300 km of fiber, (b) with optical attenuators

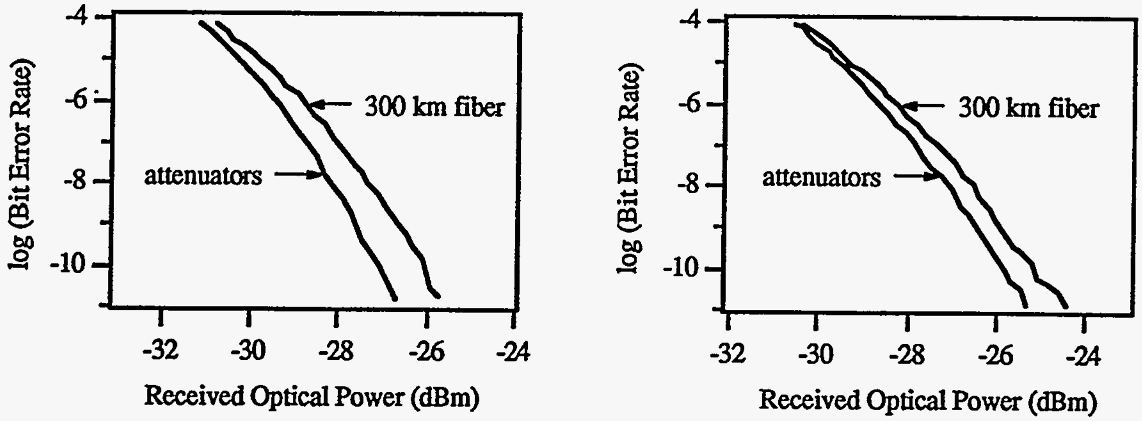

Figure 13. BER vs. received optical power for: (a) 7.3 GHz channel, (b) 14.6 GHz channel

6. SUMMARY

We have demonstrated a new dispersion-reduction technique using subcarrier multiplexing. A pair of 2.5 Gbit/s data streams were impressed onto microwave subcarriers and were successfully transmitted over 300 km of conventional single-mode fiber. We also verified the accuracy of our optical network models. Future experiments will demonstrate the compatibility of SCM with wavelength-division multiplexing (WDM).

7. ACKNOWLEDGMENTS

We thank Keith Hugenberg of Telesis Technology Labs for initiating an investigation into SCM development which formed the foundation for further advancements. We also thank Scott Young of Divicom for his assistance with SCM hardware and computer models.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. Patent pending.

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