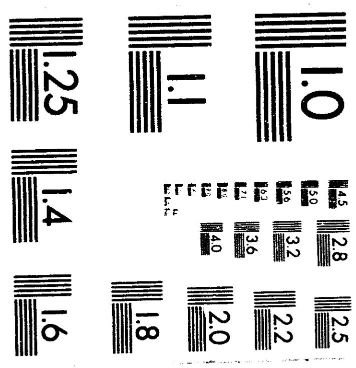
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Long Distance Transmission of 15 Gb/s Digital Using Subcarrier Multiplexing and External Modulation

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ABSTRACT

This paper provides an overview of a high-speed link design using subcarrier multiplexing techniques with external modulators. Although we have few experimental results to date, we feel the techniques and technology described in this paper will enable the simultaneous transmission of multi-channel analog video and up to 15 Gb/s of digital data on a single wavelength. Furthermore, we show preliminary modeling that would indicate that at least four channels of 2.5 Gb/s can be sent over distances exceeding 500 km using a new dispersion technique that takes advantage of subcarrier multiplexing.

I. INTRODUCTION

It is clear that as the multimedia environment continues to expand, it will become increasingly more important to use transmission methods offering both flexibility and efficient bandwidth utilization of existing network assets (principally, installed fiber). Efficient exploitation of the available fiber bandwidth is usually thought of in terms of multiplexing. Clearly, much research is currently ongoing with wavelength division multiplexing (WDM). While this technology will some day offer a many-fold multiplication of available bandwidth, there remains much development work. In this paper, we offer an alternative to WDM that may provide a more timely path to implementation, but yet is completely compatible with the eventual insertion of WDM technology. This approach is called sub-carrier multiplexing (SCM). Here, high-speed optoelectronics are integrated with microwave technology to produce sidebands on the principle laser optical carrier signal. The data can then be independently impressed upon these sidebands and simultaneously transmitted along a single fiber much as with WDM.

Subcarrier multiplexing is certainly not a new approach to the design of lightwave systems for broad-band distribution. There have been numerous published papers describing work in this area. These links have successfully utilized a large variety of analog and/or digital modulation formats, direct and coherent detection techniques, along with semiconductor laser amplifiers and erbium doped fiber amplifiers. However, the experimental systems to date have not fully exploited the recent technology advances in wide-bandwidth external modulators, erbium-doped fiber amplifiers, InGaAs detectors, and microwave amplifiers, to perform very high speed SCM in "standard" single mode fiber over long distances. (Fig. 1)

II. LINK DESIGN OVERVIEW

The term "subcarrier" is used to describe the frequency carrier (typically MHz or GHz) that is modulated by analog and/or digital signals. Subcarrier multiplexing (SCM) is the modulation of several to many frequency signals to perform multi-channel transmission. A number of baseband analog and/or digital signals are frequency division multiplexed by using local oscillators at varying frequencies. The upconverted signals from a mixer are then summed together with microwave power combiners. The aggregate signal is used to modulate either a laser diode or external modulator, depending on the application and system requirements.

The method that we selected to do the high speed digital SCM is called Quadrature (or Quaternary) Phase Shift Keying (QPSK).[1,2] This method of modulation is widely used in digital terrestrial microwave and satellite systems. However, the high frequency carriers and bit rates

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(2.488 Gb/s) are not common to these applications. Therefore, it will require a new microwave system design to be able to handle these high speeds.

The laser transmitter that will be used is either a solid-state 1540 nm YLF laser or a high power DFB laser combined with a well designed power Erbium-Doped Fiber Amplifier (EDFA). The goal is to design a high-power transmitter that will provide much longer transmission distances than currently available, while potentially taking advantage of the inherent low noise of solid-state lasers.

The modulation method we feel is best suited for transmitting both analog video (AM-VSB or FM) and digital data over relatively long distances is external modulation. There are significant performance advantages, particularly with AM-VSB video, related to the "chirp-free" behavior of external modulation.[3] Furthermore, the use of a slant polished external modulator offers superior performance when used in a link with high back reflections.[4] This is particularly important if the existing telco fiber plant is going to be used without changing all of the connectors, many of which are biconic (back reflection may be as high as 20 dB).

The current commercially available integrated-optical external modulators offer bandwidths that exceed 18 GHz. They are most commonly manufactured using substrates of $LiNbO_3$. However, there are several improvements that could be made with these devices. The first is designing a modulator with a low half-wave voltage (V_π) that is also a high speed device. The second is that the current devices have typical traveling wave electrode impedances of 30 Ohms. It is obviously more desirable to have the electrodes with a characteristic impedance of 50 Ohms. This is important for minimizing electrical reflections, maximizing power transfer, flattening out the frequency response, and removing the problem of burning out termination resistors (if used). It is the flat frequency response that is particularly beneficial in obtaining uniform channel sensitivity for broadband subcarrier multiplexing.

The external modulators to be developed at LLNL and with a manufacturer will have a low V_π (typ. < 5 V), a flat frequency response past 20 GHz (Fig. 2), a 50 Ohm traveling wave electrode (Fig. 3), and a very robust package design that will be more than capable of meeting the high standards required for use in telecommunications links. In addition, the modulators will be processed using annealed proton exchange (APE), which is much less susceptible to photorefractive damage than titanium indiffusion.[5]

Although these single modulators would perform adequately for an "all digital" SCM, another service that must be transported for the near-term future is AM-VSB video. One of the primary technical challenges of using fiber-optic systems for AM-VSB CATV is system linearity. Because intermodulation distortion is coherent (visible on the television screen) strict specifications have been defined by the CATV industry. Standard CATV system specifications require a Composite Second Order (CSO) < - 60 dBc and a Composite Triple Beat (CTB) < - 65 dBc. Aside from the limits on distortion, the system must also provide a sufficient carrier-to-noise ratio (CNR), typically > 50 dB.

In the past, some directly-modulated DFB lasers at 1.3 μm have been able to achieve these specifications for short distances, but at high costs due to their low yield and the required selection process. At the desired wavelength of 1.5 μm, both the power output and linearity fall far short of the needed performance without additional linearization compensation. Furthermore, even the use of compensation circuits have not been able to overcome the problems due to chirp over long distances [6], and the circuit's bandwidths are limited.

For these reasons, the use of externally-modulated solid-state lasers or DFB lasers coupled with optical amplifiers at 1.5 μm may offer a better alternative. Unfortunately, most external modulators have a sinusoidal transfer function and are only linear only over small depths of modulation. However, luckily, by biasing the modulator at its quadrature point, all even-order distortion is theoretically zero, leaving only odd-ordered distortions to correct. This is in contrast to the directly modulated lasers that have problems with both second and third order distortions.

To reduce the level of the third-order distortion (or CTB) of the external modulators, both electronic and optical means have been used. The electronic approaches entail predistortion circuits that compensate for the inherent non-linearity of the external modulator. The optical approaches typically use more than one modulator or light source to provide for active cancellation of the third order distortion.

The current state-of-the-art related to linearization techniques have been achieved at slightly greater than 1 GHz bandwidths. It is believed that only the optical approaches to linearization, ie. dual modulators, etc., are applicable to much wider bandwidths.[7-10] The reason for this is the lack of suitable microwave components required to do electronic linearization over multi-octave bandwidths. Therefore, the objective is to determine which of the optical approaches will achieve the best performance when bandwidths are increased above 1 GHz.

Irregardless of whether AM-VSB is supplanted in the near future by digital transmission of cable signals, the linearized modulator would provide an excellent broadband and high dynamic range component that would be superior to directly modulated laser diodes.

As we mentioned in the introduction, the current wavelength of interest for performing medium and long distance transmission over fiber is 1.55 µm. Unfortunately, a fundamental problem associated with this wavelength is dispersion. The only way to truly leverage the "infinite bandwidth" that fiber offers is to operate at 1.3 µm, to use solitons, or to compensate for dispersion in some way at 1.55 µm.

If one were to take a simplified view of chromatic dispersion at 1550 nm, the typical solution proposed for high speed transmission is the use of a narrow linewidth, single mode laser source. Unfortunately, however, even the very narrow linewidth lasers (ex. solid-state lasers), don't avoid the dispersion problem at high speeds (> 5 Gb/s) over long distances. Furthermore, the narrow linewidths in combination with high laser powers can cause nonlinear effects and distortions in the fiber that are detrimental and performance limiting, especially in a subcarrier multiplexing scenario.

For example, one of the most common nonlinear problems encountered is stimulated brillouin scattering (SBS). When the power launched into a single mode fiber reaches a critical threshold level (typ < 30 mW), SBS can occur. SBS can be crippling to an optical communications system in a number of ways. Among these are a severe limitation to the input power. In some cases, particularly long distances, the power can be limited to as low as several milliwatts.[11] Additional problems include multiple frequency shifts, high intensity backward coupling into the laser, and a potentially intense backward traveling wave that can fracture or crater the fiber.[12]

It is for these reasons, that we are pursuing a dispersion compensation solution that incorporates phase modulation. Because the SBS limit is proportional to the source linewidth, spreading the linewidth with a phase modulator has worked very well. Of course, being able to use higher power lasers will lead to a savings in the number of amplifier stages, which corresponds to huge network cost savings.

To date, the incorporation of low noise EDFAs as preamps for receiver modules has been very slow. The primary focus of the EDFA manufacturers has been on the application of in-line amplification for transatlantic cables. However, excellent sensitivity has been achieved in laboratory experiments with non-optimized EDFAs used as preamps.[13] It is in this vein, that we will work very closely with an EDFA manufacturer to come up with the optimal design for incorporating the EDFAs into such a preamp configuration.

Furthermore, to fully complement the receiver module for use in an SCM network, we will integrate a high-speed detector with a low noise amplifier to achieve bandwidths from DC-20 GHz. In anticipation of Wavelength Division Multiplexing (WDM), the receiver module will also include state-of-the-art Fiber Fabry-Perot (FFP) Filters with losses less than 0.5 dB and finesses as high as 300. They are designed for extremely narrow bandwidths, which significantly reduce the Amplified Spontaneous Emission (ASE) noise produced by the EDFA, and they have phase locked loop capability for maintaining the proper wavelength. The signal gain we receive from the EDFAs in conjunction with the FFP filters for noise removal should provide receiver sensitivities exceeding - 40 dBm. In summary, all of these components together will provide a very flexible, robust, and superior detection module for use in SCM or other transmission schemes.

III. MODELING AND EXPERIMENTAL RESULTS

As regards to providing dispersion compensation at 1.55 µm for standard single mode fiber, we are currently researching several promising possibilities through the help of a model developed at LLNL. The preliminary modeling results of a "passive" technique look very good. (to be published at a later date) The plot of 2.5 Gb/s data modulating a 15 GHz subcarrier is shown in Fig. 4. Note that the distance traveled is 500 km, and that by using QPSK modulation, the aggregate digital speed transmitted is 10 Gb/s (ie. 4 channels at 2.5 Gb/s). That is quite an improvement over the nominal 35 km distance limitation of a 10 Gb/s baseband transmission in "non-compensated" single mode fiber at 1550 nm.[14] Furthermore, by using the additional 8 GHz of bandwidth available from the modulator, there is potential for the transmission of > 15 Gb/s of digital data. (Fig. 5)

The experimental set-up used to initially demonstrate SCM at high carrier frequencies is shown in Fig. 6. Figs. 7 and 8 show, at least in principle, the SCM performance of a LLNL $LiNbO_3$ modulator at 1320 nm. Due to the lack of the high-speed QPSK modulators at the time of this demonstration, we chose to perform standard amplitude modulation (400 MHz) on 10 and 15 GHz carriers. Also, note that we used a $LiNbO_3$ modulator to perform the actual modulation of the carrier signals. However, as we described previously, in the link design we are proposing, all of the modulation and demodulation of the subcarriers will be done with high speed microwave and electronics components.

IV. CONCLUSION

In summary, we feel that this paper outlines system components and technology that could significantly impact the current and future multimedia networks. SCM systems are ideal for providing both the system flexibility and efficient bandwidth utilization that will be required. SCM is also one of the few techniques that can transmit the future network's vast array of services in a cost effective manner. Finally, and probably most importantly, SCM is and will be completely compatible with TDM, wavelength division multiplexing (WDM), erbium doped fiber amplifiers (EDFA), SONET, and asynchronous transfer mode (ATM) as these technologies become more mature and are implemented more extensively into fiber networks.

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Keith Hugenberg received the B.S. and M.S. Degrees in electrical engineering from the Georgia Institute of Technology in 1987 and 1988, respectively, with specialties in optics and fiber optics. His work at LLNL has involved the design and development of high power laser systems, specialized measurement systems, and high-speed photonics systems for data acquisition of Nuclear Tests. His current position is a Lightwave Systems Engineer for the Photonics Group in the Center of Microelectronics and Optoelectronics. His research activities include multi-wavelength optical networks using EDFA's and the applications of external modulators to high-speed fiber optic analog and digital links for LAN's and WAN's.

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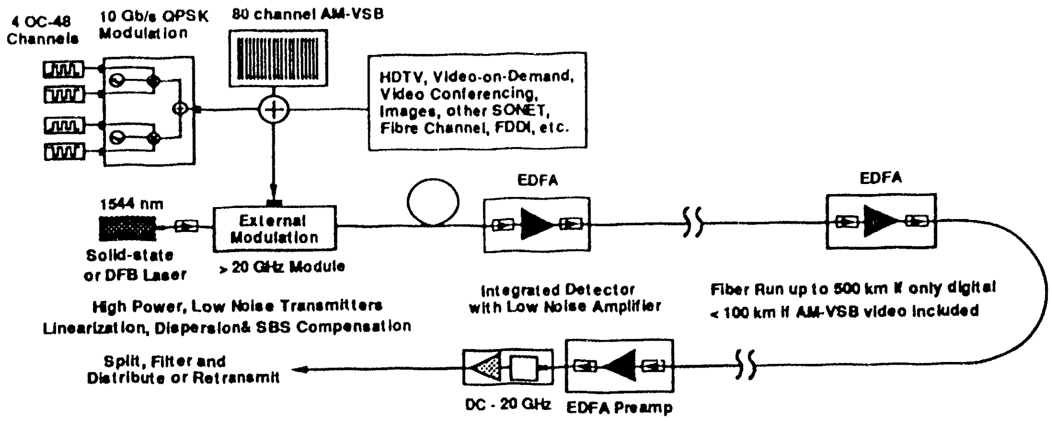

Fig. 1 Subcarrier Multiplexing link design for transmitting multi-media services and high-speed digital long distances.

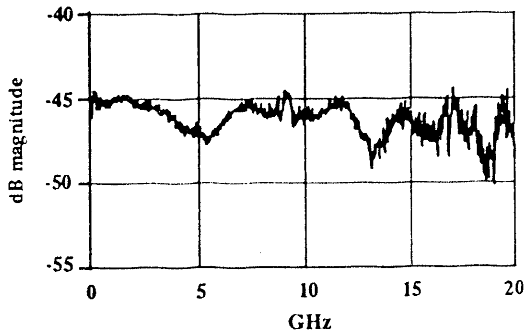

Fig. 2 Typical frequency response of a LLNL external modulator

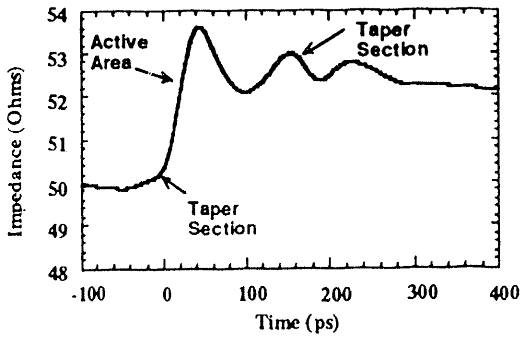

Fig. 3 Impedance of the traveling wave electrode of a LLNL external modulator

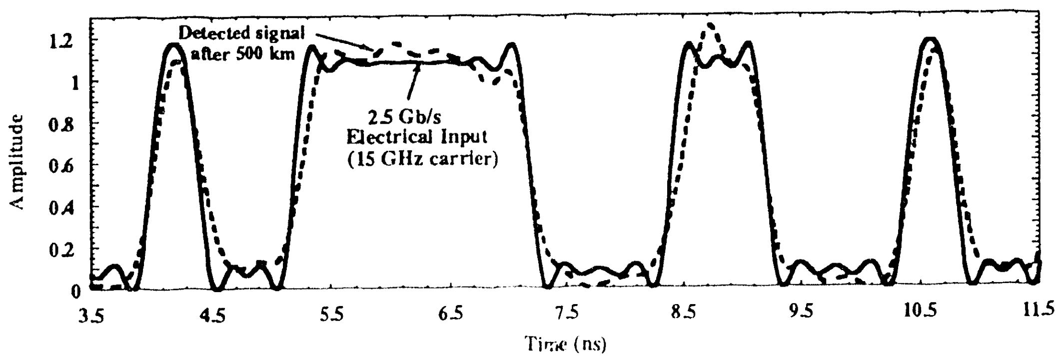

Fig. 4 Modeling results of a new dispersion compensation method. The figure demonstrates how well the 2.5 Gb/s electrical input agrees with the detected signal after traveling 500 km on single mode fiber.

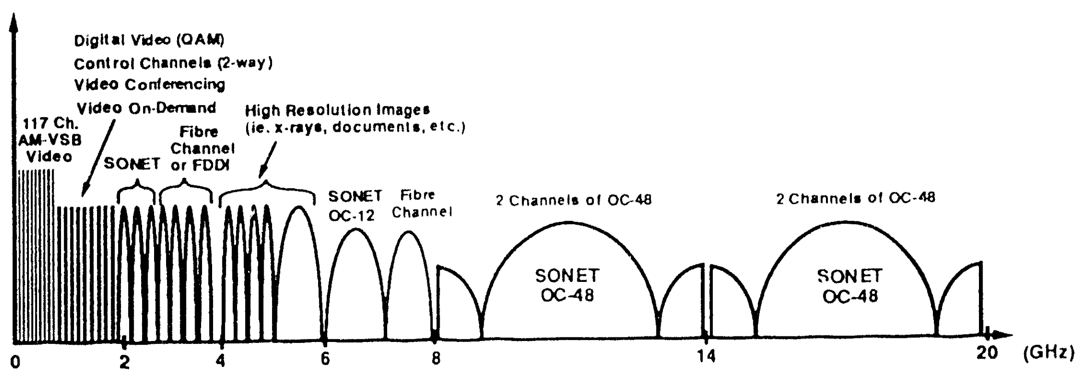

Fig. 5 Frequency domain example showing the power and flexibility of SCM to transmit multimedia.

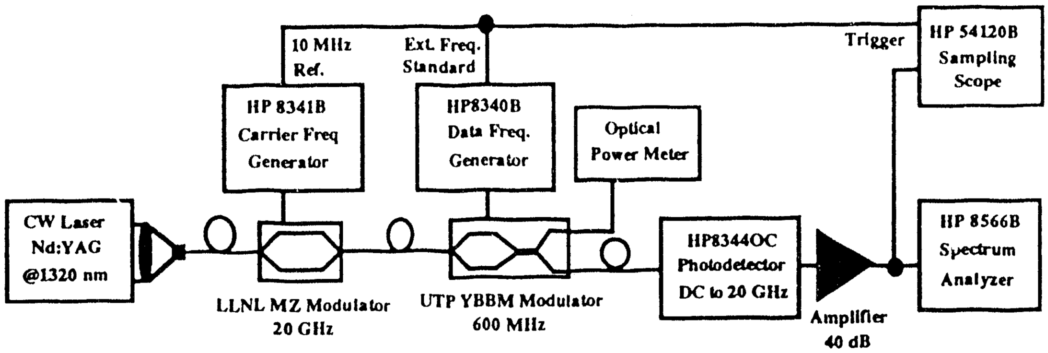

Fig. 6 Block diagram for doing SCM using two external modulators. This set-up was used to acquire the data in Figs. 7 & 8.

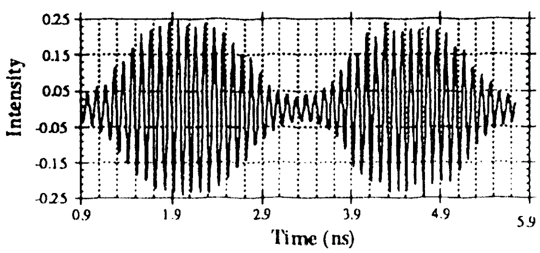

Fig. 7 Detected signal of a 10 GHz carrier modulated by a 400 MHz sine wave.

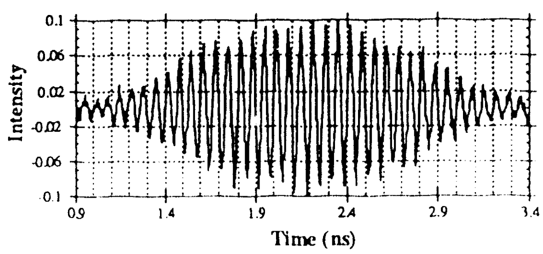

Fig. 8 Detected signal of a 15 GHz carrier modulated by a 400 MHz sine wave.

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