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33-Channel 64-QAM Signal Transmission Using a 1.3-μm Semiconductor Optical Amplifier

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***Abstract*— From the network evolution point of view, optical amplifiers in a hybrid fiber coaxial (HFC) system may become extensively deployed at approximately the same time as when analog AM-VSB video signals are all replaced by digital M-QAM or M-VSB signals. This letter demonstrates the feasibility of using a 1.3-μm semiconductor optical amplifier to transport 33 channels of 64-QAM signals with 30 Mbps/channel. A total system power budget of 20.3 dB was obtained.**

I. INTRODUCTION

TWO important facts determine the design of today's CATV or hybrid fiber coaxial (HFC) systems. The first is that almost all optical fibers deployed are 1.3 μm zero-dispersion single-mode fibers (SMF's), and the second is that thousands of 1.3 μm distributed-feedback (DFB) laser transmitters and external modulation systems have been installed. All the existing 1.3 μm SMF's and 1.3 μm optical transmitters will continuously be used in their long lifetime. On the other hand, 1.55 μm transmitters have not been installed as widely as their 1.3 μm counterparts. Therefore, for deeper fiber penetrations, using 1.55 μm erbium-doped fiber amplifiers (EDFA's) may not be as economically viable as using 1.3 μm optical amplifiers. In addition, the high fiber dispersion (17–20 ps/km/nm) incurred by a 1.55 μm light beam in a 1.3 μm SMF can induce severe second-order nonlinear distortions (NLD's) [1] and consequently limit the transmission distance. These system issues have motivated many researchers to work on 1.3 μm praseodymium-doped fluoride fiber amplifiers [2] and Raman amplifiers [3]. However, the pump efficiency and cost factors of these amplifiers remain to be solved.

It is interesting to note that semiconductor optical amplifiers (SOA's) have long been considered not suitable for CATV systems which transmit multi-channel AM-VSB video signals. The main reason is due to the carrier-density-modulation induced second order NLD's [4], [5]. However, despite the fact that these second-order NLD levels cannot be tolerated by AM-VSB signals, they may be acceptable to subcarrier-multiplexed digital video channels using M-ary quadrature-amplitude-modulation (M-QAM) or digital M-ary vestigial-sideband modulation (M-VSB). With the vast development of M-QAM and M-VSB modems for CATV systems, it can be foreseen that all of the present multi-channel AM-VSB signals will eventually be replaced by M-QAM or M-VSB modulated MPEG II video signals. Parallel to this evolution process is the penetration of optical fibers which will not be restricted to only trunk lines. Therefore, the potentially low-cost 1.3 μm semiconductor optical amplifiers may play an important role in these digital lightwave CATV systems [6]. In this paper, we present the first feasibility demonstration of transporting 33 channels of 64-QAM subcarrier-multiplexed signals by using a 1.3 μm semiconductor optical amplifier.

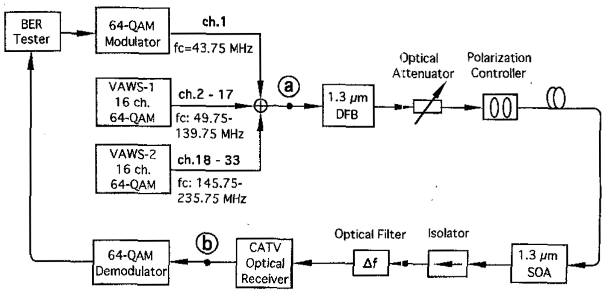

Fig. 1. Experimental setup.

II. SYSTEM EXPERIMENT

The 33 channels of 64-QAM signals were constructed using three sets of equipment as shown in Fig. 1. Channel 1 was generated from a 30 Mbps 64-QAM modulator with a center frequency of 43.75 MHz. Channels 2 to 17 were generated from a vector arbitrary waveform synthesizer (VAWS) whose input data came from a waveform generation software. VAWS is composed of two 12-bit digital-to-analog converters (DAC's) with a sampling rate of 125 Msps and a vector signal modulator. In the waveform generation software program, we have carefully randomized the carrier phase among different carriers and ensured that the channel separation be exactly 6 MHz. Channels 18 to 33 were generated from a second set of VAWS system. Each 64 QAM channel from VAWS had a pattern length of 1024. The spectrum of the combined 33 channels of QAM signals is shown Fig. 2(a). Great care has been taken to eliminate spurious signals due to the DAC's in VAWS. The combined signals were then used to modulate a typical 1.3 μm CATV laser transmitter which has an output power of 10.6 dBm. The laser transmitter can transport 60

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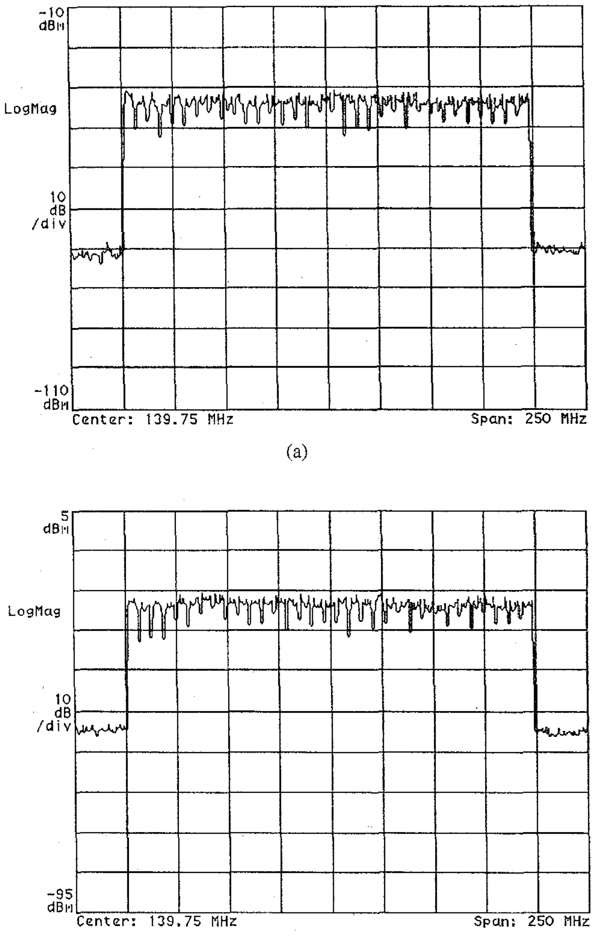


(a)

(b)

Fig. 2. Spectra of (a) transmitted and (b) received 33-channel 64-QAM signal at $P_{in} = -9.7$ dBm.

channels of AM-VSB signals with CTB < -65 dBc, CSO < -65 dBc, and CNR ≈ 50 dB. The InGaAs PIN-diode-based CATV optical receiver has a bandwidth of 550 MHz and an equivalent input thermal noise current density of 7 pA/$\sqrt{\text{Hz}}$. As shown in Fig. 1, an adjustable optical attenuator, a polarization controller with an insertion loss of 0.11 dB, a commercially available 1.3 μm SOA, an optical isolator with an insertion loss of 0.8 dB, and an optical filter with a 3-dB bandwidth of 1.7 nm and an insertion loss of 4.4 dB were inserted between the laser transmitter and the optical receiver. The polarization controller was required to optimize the optical gain and output saturation power of the SOA. The SOA has a small-signal fiber-to-fiber gain of 8 dB and a poor noise figure of about 8.5 dB at a bias current of 100 mA.

The spectrum of the received 33-channel 64-QAM signals is shown in Fig. 2(b). Comparing this spectrum with Fig. 2(a), we can see that the noise level has been increased by about 5 dB. This increase of noise level is mainly due to signal-spontaneous beat noise, multiple-reflection (between the SOA facets) induced interferometric noise, and intermodulation products which spread out like noise. It should be noted that the SOA noise figure was defined as $(S/N)_{out}/(S/N)_{in}$ when $(S/N)_{in}$ is shot-noise limited. Therefore, even though our SOA noise figure was as high as 8.5 dB, the net result given in Fig. 2

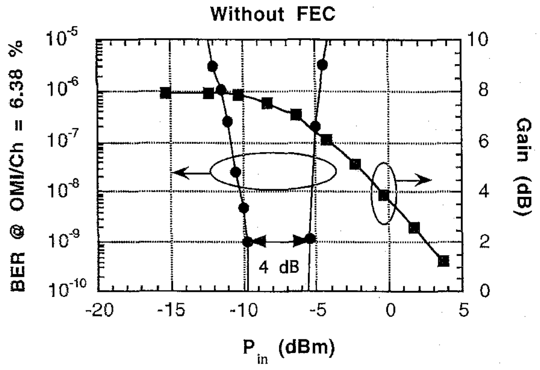
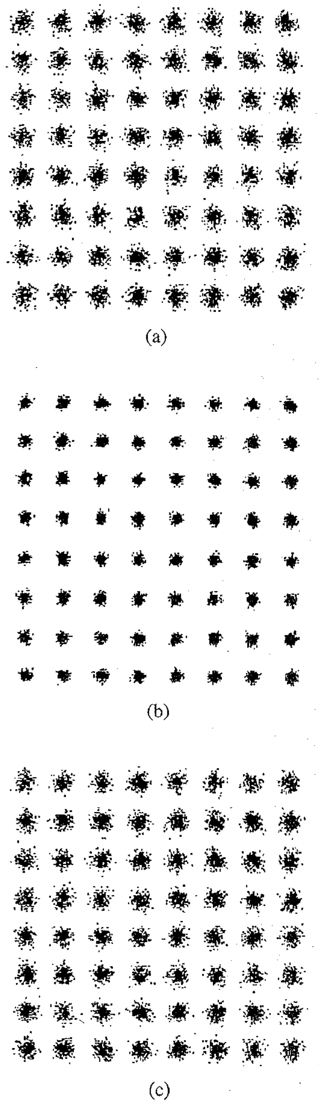


Fig. 3. BER and SOA gain versus SOA input power (P_{in}). The dynamic range for BER $\leq 10^{-9}$ is about 4 dB for a 30 Mbps 64-QAM modem without forward error correction.



(a)

(b)

(c)

Fig. 4. Constellation diagrams of the received channel 1 signal when SOA input power levels are (a) -4.5 dBm, (b) -6.5 dBm, and (c) -12.5 dBm, respectively. OMI/Ch = 6.38%.

showed a SNR degradation of only 5 dB. This is because $(S/N)_{\text{in}}$ in Fig. 2(a) includes the effect of not only shot noise but also the thermal noise from VAWS system.

Since the carrier-density-modulation-induced second-order NLD's due to a saturated SOA degrade the edge-channel signal performance most seriously [4], [5], we chose channel 1 to test its bit-error-rate (BER) with a pseudo-random data whose pattern length is $2^{23}-1$. The BER performance as a function of the optical input power (P_{in}) to the SOA is shown in Fig. 3. It can be seen that when P_{in} is low, the BER performance was poor due to the dominance of signal-spontaneous beat noise. When P_{in} is high, however, BER performance also degraded due to the increase of second-order NLD's. Therefore, the SOA has an input dynamic range of about 4 dB within which the BER is below 10^{-9}, as indicated in Fig. 3. In the same figure, the gain versus P_{in} curve of the SOA is shown. We can see that the 4 dB dynamic range is mostly within the 2-dB gain saturation region of the SOA. Note that this dynamic range can be significantly improved if 1) multiple-reflection-induced interferometric intensity noise can be reduced by low-reflectivity SOA facets or by using external modulation technique, and 2) forward-error-correction codecs can be built into the 64-QAM modem. Fig. 4 illustrates the constellation diagrams (measured after the analog-to-digital converter in the 64-QAM demodulator) of the 64-QAM signal for three different P_{in} conditions, i.e., -4.5 dBm (BER $\approx 10^{-5}$), -6.5 dBm (BER $< 10^{-10}$), and -12.5 dBm (BER $\approx 10^{-5}$). It can be seen that the effect of NLD's is similar to that of signal-spontaneous beat noise. This is due to multi-channel QAM signals spread out like white noise. At $P_{\text{in}} = -9.7$ dBm, a total system power budget (between the laser transmitter and the SOA preamplifier) of 20.3 dB was obtained. Note that the total power budget for the back-to-back link without SOA was 16.6 dB (with the transmitter power of 10.6 dBm and the receiver sensitivity at 64-QAM BER $= 10^{-9}$ of -6 dBm).

III. CONCLUSION

We have successfully demonstrated the feasibility of using a 1.3 μm semiconductor optical amplifier to transport 33 channels of 30 Mbps 64-QAM signals. The limited SOA input power dynamic range can be further improved by reducing the multiple-reflection induced interferometric noise and by using forward error correction codecs. As the vast development of set-top boxes with built-in M-QAM (or M-VSB) modems and the penetration process of deploying optical fibers both continue, the system technologies demonstrated in this paper may provide a practical transmission solution.

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