Eight-Way, 70-km Transmission of 33-Channel 64-QAM Signals Utilizing a 1.3-μm External Modulation System and Semiconductor Optical Amplifier

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***Abstract*—By using a 1.3-μm external modulation system and a semiconductor optical amplifier, we experimentally demonstrated the feasibility of broadcasting 33 channels of 64-QAM digital CATV signals to eight 70-km optical fiber links. The presented results show that, with the vast momentum on developing M-QAM modems, potentially low-cost semiconductor optical amplifiers can possibly expedite the penetration pace of optical fibers in broad-band access networks.**

I. INTRODUCTION

ALL the 1.3-μm zero-dispersion single-mode fibers (SMF's) and 1.3-μm optical transmitters in today's CATV networks will be used continuously over a long period of time. Therefore, when a larger optical power budget is required for deeper fiber penetrations in the near future, using 1.3-μm optical amplifiers may be more economically and technically viable than using 1.55-μm erbium-doped fiber amplifiers (EDFA's). Parallel to the evolution process of deep fiber penetration in the subscriber loop will be the matured development of M-ary quadrature-amplitude-modulation (M-QAM) modems and MPEG-II codecs and the gradual replacement of all AM-VSB video channels by M-QAM digital video channels. Consequently, it is of great interest to see if potentially low-cost semiconductor optical amplifiers can be used to transport multiple channels of ITU-standardized 64-QAM signals. The feasibility of transmitting 33 channels of 64-QAM signals by using a directly modulated 1.3-μm DFB laser and a semiconductor optical amplifier has been recently demonstrated [1]. In this letter, we demonstrate that the system power budget can be significantly increased by using an external modulation system [2].

II. SYSTEM EXPERIMENT

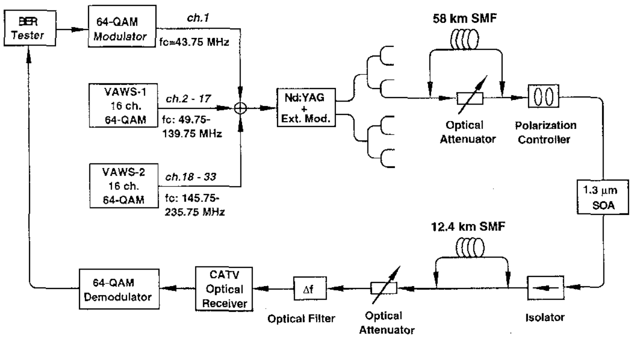

Fig. 1. Experimental setup.

Fig. 1 shows the experimental setup. The 33 channels of 64-QAM signals were constructed using three sets of equipment. Channel 1 was generated from a 30-Mb/ps 64-QAM modulator with a center frequency of 43.75 MHz. Channels 2–17 were generated from a vector-arbitrary waveform synthesizer (VAWS) whose input data came from a waveform generation software package. VAWS is composed of two 12-bit digital-to-analog converters (DAC's) with a sampling rate of 125 Ms/ps 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 is exactly 6 MHz. Channels 18–33 were generated from a second set of VAWS system. Each 64-QAM channel from VAWS had a pseudorandom symbol pattern length of 2^{10}. Great care was taken to eliminate spurious signals due to the DAC's in VAWS. The combined signals were then used to modulate a 1.3-μm $LiNbO_3$ balanced-bridge interferometer (BBI) modulator [3] which has dual outputs. By using a high-power 1.319-μm Nd:YAG laser, both optical outputs of the modulator reached $+13$ dBm. The BBI modulator had built-in predistortion and bias-control circuits, and could transport 60 channels of AM-VSB signals to the InGaAs PIN-diode-based CATV optical receiver with a typical performance of CTB < -65 dBc, CSO < -65 dBc, and CNR ≈ 50 dB, for a received optical power > -3 dBm. Between the external modulator and the optical receiver are, 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 3.7 nm and an insertion loss of 1.7 dB. The polarization controller was required to optimize the optical gain and output saturation power of the SOA. The SOA had a noise figure of about 7.5

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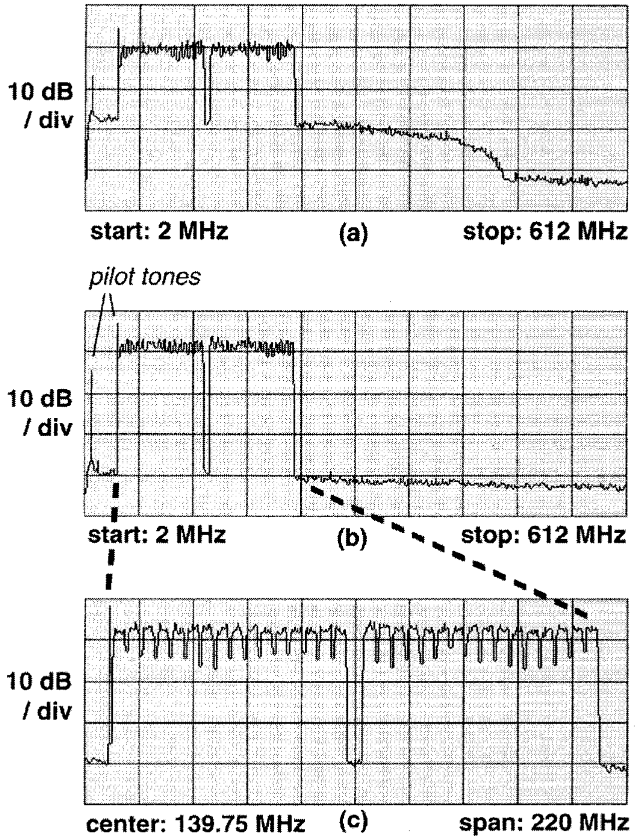
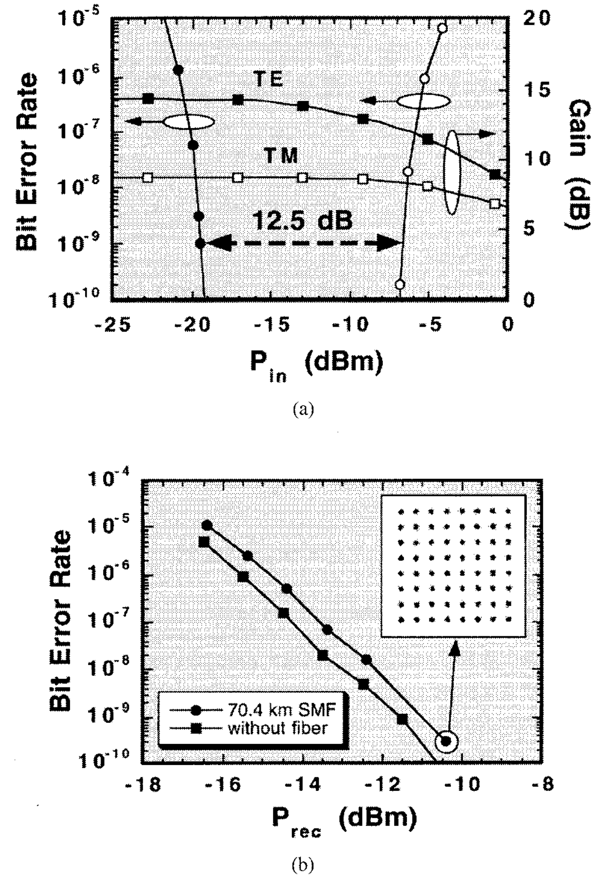


Fig. 2. Spectra of received 33-channel 64 QAM signals (with the middle channel turned off) at $P_{\rm in}$ = (a) 0 dBm and (b) −11 dBm. (c) is the expanded view of (b). OMI/ch = 6.38%.

dB in its linear gain region at a bias current of 100 mA.

The spectra of the received 33-channel 64-QAM signals at two input power levels to the SOA ($P_{\rm in}$) are shown in Fig. 2(a) ($P_{\rm in}$ = 0 dBm) and 2(b) ($P_{\rm in}$ = −11 dBm), respectively. Fig. 2(a) shows the high level of carrier-density modulation-induced second-order nonlinear distortions [4] (NLD's) when the SOA was operated in gain saturation. In contrast, Fig. 2(b) and (c) exhibit no NLD products, and the average −30-dBc noise level was mainly due to the signal-spontaneous beat noise. The middle channel in Fig. 2 was purposely turned off to show that the noise and NLD's contained in the middle channel were at about the same level as those contained in the edge channels. Therefore, we chose channel 1 to test its bit-error rate (BER) with a pseudorandom data whose pattern length was $2^{23}-$ 1. The BER performance as a function of $P_{\rm in}$ is shown in Fig. 3(a). It can be seen that when $P_{\rm in}$ is low, the BER performance was poor due to signal-spontaneous and spontaneous-spontaneous beat noise. When $P_{\rm in}$ is high, however, BER performance also degraded due to the increase of second-order NLD's [4], [5]. Therefore, the SOA has an input dynamic range of about 12.5 dB within which the BER is below 10^{-9}. In the same figure, the TE and TM gain curves of the SOA are also shown. Note that the BER curves were obtained by controlling the polarization to increase SOA gain at low $P_{\rm in}$ (using TE) or to increase the saturation output power at high $P_{\rm in}$ (using TM). We can see that the 12.5-dB dynamic range is within the linear region of the SOA. Note that this dynamic range can be slightly improved if forward-error-correction codecs can be built into the 64-QAM modem. Fig. 3(b) illustrates the BER curves and the constellation diagram of the 64-QAM signal with and without the 58 km and 12.4 km of SMF's placed before and after the SOA, respectively, as shown in Fig. 1. The dispersion penalty of about 0.5 dB is within the measurement uncertainty. Since each of the external modulator's output power was split four times before launching into the SMF, we have a total of eight links, with each link budget of about 26.8 dB (0.38 dB/km × 70.4 km). By replacing the SMF's with tunable optical attenuators and finding the optimum $P_{\rm in}$, each link budget can be increased by another 3 dB.



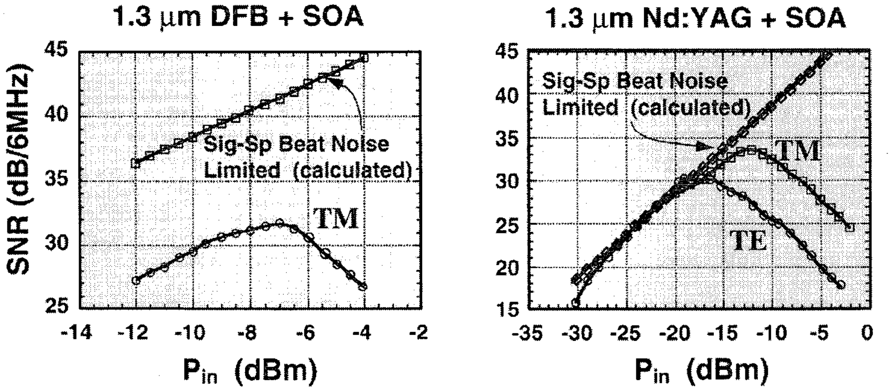
(a)

(b)

Fig. 3. (a) BER and SOA gain versus SOA input power ($P_{\rm in}$). (b) BER versus received optical power ($P_{\rm rec}$) and the received 64-QAM constellation diagram when 58 km and 12.4 km SMF's were placed before and after the SOA, respectively.

III. DISCUSSION

Comparing with our previous experiment, which used a directly modulated DFB laser [1], we found that the input dynamic range of the SOA can be increased from 4–12.5 dB for the same optical modulation index (OMI) per QAM channel of 6.38%. The poor dynamic range in a direct-modulation system was mainly due to the amplified multiple



(a) (b)

Fig. 4. SNR versus SOA input power (P_{in}) for (a) direct modulation system and (b) external modulation system, respectively. The signal-spontaneous noise-limited SNR was calculated by using the following parameters: input coupling loss = −4.5 dB, noise figure = 7.5 dB, OMI/channel = 6.38%.

reflection-induced RIN noise [6] and second-order nonlinear distortions [7]. The amplified multiple reflections were caused by the combination of laser frequency chirping, SOA facet reflectivities ($\approx 10^{-3}$), and SOA gain. The multiple reflections are negligible in the external modulation system because of the narrow linewidth (≈10 KHz) of the Nd:YAG laser. To examine this phenomenon, we plotted SNR (per QAM channel) versus P_{in} (of the SOA) for both direct and external modulation systems in Fig. 4. We can see that when P_{in} is small, the measured SNR in the external modulation system is mainly limited by the signal-spontaneous beat noise ($N_{\mathrm{sig\text{-}sp}}$), while there are about 9-dB discrepancies between the calculated $N_{\mathrm{sig\text{-}sp}}$-limited and the measured SNR in the direct modulation system. These large discrepancies were mainly due to the SOA amplified multiple reflections. Note that in Fig. 4, SNR degrades at large P_{in} due to SOA-gain saturation-induced second-order distortions, which set the fundamental system limitation.

IV. CONCLUSION

We have successfully demonstrated the feasibility of using a 1.3-μm external modulation system and a semiconductor optical amplifier to broadcast 33 channels of 30 Mbps 64-QAM signals to eight 70-km optical fiber links. We pointed out that the SOA input dynamic range in an Nd:YAG external modulation system can be significantly increased compared with that of a direct modulation system, mainly owing to the absence of multiple-reflection-induced RIN and second order distortions. We also pointed out that when the input power to the SOA is large, it is the carrier-density modulation-induced second-order nonlinear distortions that set the fundamental system limitation in delivering multiple channels of 64-QAM signals. In addition, SOA parameters such as high-output saturation power, low-noise figure, polarization independence, and low-facet reflectivities are critical for improved systems performance.

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