Reduction of Nonlinear Distortion in MQW Semiconductor Optical Amplifier Using Light Injection and its Application in Multichannel M-QAM Signal Transmission Systems

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***Abstract*— By using an external light-injected multiple-quantum-well (MQW) semiconductor optical amplifier (SOA), we have demonstrated a 100-km optical fiber link that transports 77 channels of 64-QAM signals. This is equivalent to a system capacity of 2.3 Gb/s, while using a laser bandwidth of only 550 MHz. Under a requirement of carrier to noise and nonlinear distortion ratio of 30 dB per channel, the 1310-nm gain-peaked SOA input dynamic range was increased from 0 to 9 dB due to an injected light with 8.8 dBm and a wavelength of 1284 nm.**

***Index Terms*— M-QAM CATV transmission system, MQW semiconductor optical amplifiers, nonlinear distortion.**

I. Introduction

THE FEASIBILITY of using semiconductor optical amplifiers (SOA's) to transport multiple 64-QAM channels for high-capacity digital video and data transmissions was demonstrated recently [1], [2]. However, the system transmission distance and channel capacity require further improvement due to the limited SOA input dynamic range. This limitation is mainly due to the gain-saturation-induced carrier density modulation and the resultant nonlinear distortions (NLD's). In the past, linearization schemes such as feedforward [3], bias current feedback [4], and the utilization of gain-clamped SOA [5], have been proposed to reduce the gain-saturation-induced NLD's. In this letter, we propose an alternative technique, i.e., using pumping light injection, to increase the saturation output power and the dynamic range of a multiple-quantum-well (MQW) SOA. This technique has been shown to effectively increase the SOA output saturation power [6] and has been tested in a multigigabit wavelength-division-multiplexed (WDM) system [7].

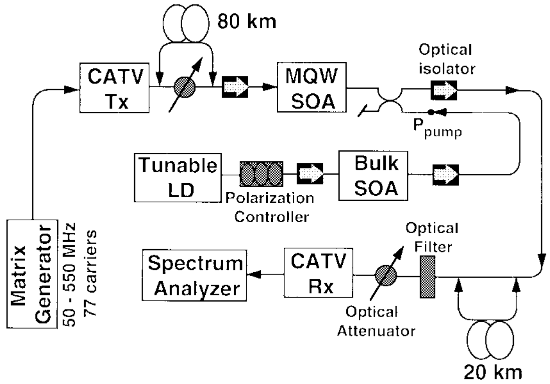

Fig. 1. Experimental setup.

The basic physics of the pumping light injection technique is that the injected light increases the SOA stimulated recombination rate, which results in decreased carrier lifetime and increased gain recovery rate [6], [8]. In addition, the saturation output power was shown to be nearly inverse proportion to carrier lifetime [6]. The wavelength of the pumping light, however, must be carefully selected at the edge of the SOA gain spectrum, in order to avoid a large unsaturated optical gain reduction [6].

In this letter, we use the pumping light injection technique to increase the input dynamic range of a MQW SOA, and successfully carry out a 100-km transmission experiment in which 77 channels of 30-Mb/s 64-QAM signals (equivalent to a capacity of 30 Mb/s × 77 $\approx$ 2.3 Gb/s) can be transported [9].

II. System Experiment

Fig. 1 shows the experimental setup. Seventy-seven random-phased continuous-wave (CW) carriers with 6 MHz spacing (starting from 55.25 MHz), from a Matrix generator, were used to simulate 77 channels of 64-QAM signals [10]. These carriers were used to directly modulate a 1.3 μm distributed-feedback (DFB) laser-based CATV transmitter which has an output power of 13.3 dBm. The laser transmitter can transmit 80 channels of AM-VSB NTSC signals to an InGaAs PIN-diode-based optical receiver with a typical performance of composite triple beat (CTB) < -67 dBc, composite second order (CSO) < -63 dBc, and carrier-to-noise ratio (CNR) $\approx$ 50 dB, for a received optical power > -1

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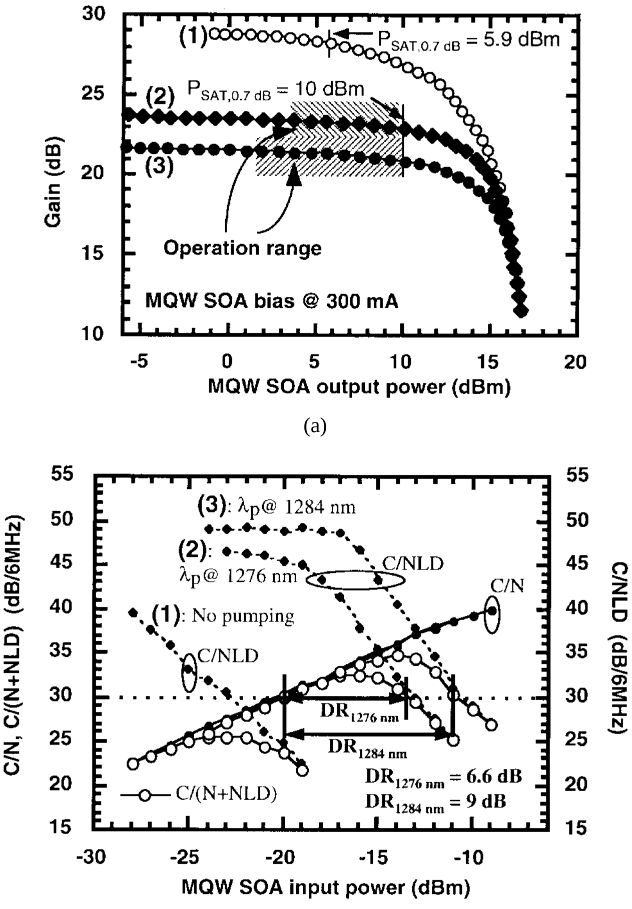

(a)

(b)

Fig. 2. (a) Fiber-to-fiber gain at 1310 nm versus MQW SOA output power, and (b) measured $C/N, C/NLD$, and $C/(N+NLD)$ of channel #1 as a function of the MQW SOA input power ($P_{\rm in}$,) for three different operation conditions: (1) without pumping, (2) with external backward pumping ($\lambda_p =$ 1276 nm, $P_{\rm pump}$ = 8.8 dBm), and (3) with external backward pumping (λ_p = 1284 nm, $P_{\rm pump}$ = 8.8 dBm).

dBm. The commercially available MQW SOA, which has a low polarization sensitivity (≈0.5 dB) and a low gain-ripple performance (<0.3 dB), was backward pumped through a 3-dB coupler by a bulk-SOA-amplified tunable laser transmitter. Between the 3-dB coupler and the optical receiver are, as shown in Fig. 1, an optical isolator with an insertion loss of 0.83 dB, an optical filter with a 3-dB bandwidth of 1.7 nm and an insertion loss of 2.7 dB, and an adjustable optical attenuator. At a bias current of 300 mA, the fiber-to-fiber gain peaks at 1310 nm, and its value as a function of MQW SOA output power is shown in Fig. 2(a). Specifically, without light injection [case (1) in Fig. 2(a)], the SOA had a small-signal fiber-to-fiber gain (G_S) of 28.9 dB; with a pumping light of $P_{\rm pump}$ = 8.8 dBm, G_S was reduced to 23.7 and 21.7 dB for pumping wavelengths of λ_p = 1276 nm [case (2)] and 1284 nm [case (3)], respectively. The SOA noise figure in the small-signal region remains essentially unchanged (≈8 dB) with and without pumping light injection. In both of the above pumping conditions, the 0.7-dB saturation output power ($P_{\rm SAT,\,0.7\,dB}$) can be increased by ~4.1 dB, as can be seen in Fig. 2(a). Consequently, the SOA input dynamic range can be increased.

In the transmission system experiment, each 64-QAM signal requires a 30-dB carrier-to-noise and nonlinear distortion ratio ($C/(N+NLD)$) to achieve a bit-error-rate of 10^{-9}, where N represents the noise contributions mainly from signal-spontaneous beat noise, multiple-reflection-induced RIN, and receiver thermal noise; and NLD represents SOA gain-saturation-induced intermodulation products (which can be treated as white Gaussian noise for the case of multiple 64-QAM signals) [1], [2]. Therefore, for an SOA used for multichannel 64-QAM transmissions, its input dynamic range is defined as the range of input optical power $P_{\rm in,min} \le P_{\rm in} \le P_{\rm in,max}$, where $P_{\rm in,min}$ is the minimum input optical power to meet $C/N \ge$ 30 dB, and $P_{\rm in,max}$ is the maximum input power to meet carrier-to-nonlinear distortion ratio $(C/NLD) \ge$ 30 dB.

The measured $C/N, C/NLD$, and $C/(N+NLD)$ of channel #1 (whose carrier is at 55.25 MHz) as a function of $P_{\rm in}$ are shown in Fig. 2(b) and were obtained under the same three operating conditions as in Fig. 2(a): case (1) (without pumping), case (2) (with λ_p = 1276 nm, $P_{\rm pump}$ = 8.8 dBm), and case (3) (with λ_p = 1284 nm, same $P_{\rm pump}$), respectively. Fig. 2(b) were measured when optical modulation index (OMI) per channel was 5%. We can see that the input dynamic range (DR) was increased from 0 dB [case (1)] to 6.6 dB [case (2)] and 9 dB [case (3)], respectively. These improvements are due to the light-injection-induced rightward shift of the C/NLD versus $P_{\rm in}$ curve, which is a result of the increased saturation power. The suitable operation range of $P_{\rm in}$ shown in cases (2) and (3) can be translated to the corresponding operation range of $P_{\rm OUT}$, as highlighted in Fig. 2(a). It is interesting to note that we must have $P_{\rm OUT} \le P_{\rm SAT,0.7\,dB}$, for both pumping wavelengths, in order to achieve the required $C/(N+NLD)$ for each 64-QAM signal. This requirement, however, is not as stringent as what was required by multichannel AM-VSB video transmissions, i.e., the optical gain must be kept constant within 0.1 dB or less [5].

The requirement of $P_{\rm OUT} \le P_{\rm SAT,0.7\,dB}$ can be used to explain why the MQW SOA had zero input dynamic range when no pumping light was applied: according to case (1) in Fig. 2(b), we know that $P_{\rm in}$ must be kept greater than −20 dBm to meet $C/N \ge$ 30 dB. However, the condition $P_{\rm in} \ge -20$ dBm corresponds to $P_{\rm OUT} \ge$ 7.7 dBm [see Fig. 2(a)], which is beyond the 0.7-dB gain saturation point.

From Fig. 2(b), it is noted when λ_p = 1284 nm (26 nm away from the gain peak) was chosen, the SOA dynamic range would be greater than that of λ_p = 1276 nm (34 nm away from the gain peak) by 2.4 dB. This difference is mainly due to the difference between the reduced small-signal SOA gains (23.7 − 21.7 = 2 dB) at the two pumping wavelengths. If the maximum allowable $P_{\rm OUT}$ ($\le P_{\rm SAT,0.7\,dB}$) is the same in both cases [which is true as Fig. 2(a) shows], the smaller gain at λ_p = 1284 nm can allow higher $P_{\rm in}$, and consequently increases the SOA dynamic range. The other 0.4 dB more dynamic range at λ_p = 1284 nm can be attributed to the smaller slope of the optical gain versus $P_{\rm OUT}$ curve at $P_{\rm SAT,0.7\,dB}$ [5].

Fig. 3(a) illustrates the measured $C/(N+NLD)$ of channel #1 after 100-km transmission of standard single-mode fibers (SMF's). The length of the optical fibers before and after the SOA were 80 and 20 kilometers, respectively (see Fig. 1). The

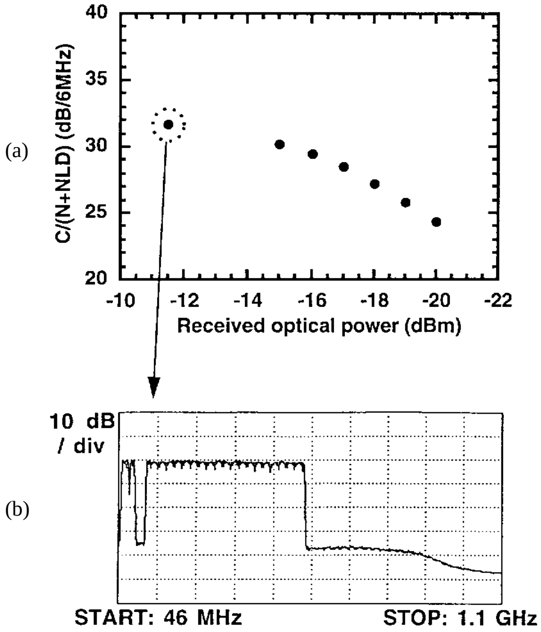

Fig. 3. (a) The measured $C/(N+NLD)$ of channel #1 versus received optical power. (b) The received RF spectrum, when 80 and 20 km SMF's were placed before and after the MQW SOA. Optical pumping was at $\lambda_p =$ 1284 nm and $P_{\text{pump}} = 8.8$ dBm. The resolution bandwidth of the spectrum analyzer was 3 MHz.

SOA (pumped at $\lambda_p = 1284$ nm with $P_{\text{pump}} = 8.8$ dBm) input and output optical power were −17.6 and 3.6 dBm, respectively. The RF spectrum of the received 77-channel video signals at a received optical power (P_{rec}) of −11.5 dBm is shown in the Fig. 3(b). At $P_{\text{in}} = -17.6$ dBm and $P_{\text{rec}} = -15$ dBm (where $C/(N+NLD) \approx 30$ dB), the total link budget (between laser transmitter and receiver) was about 49.5 dB [13.3 − (−17.6) + 3.6 − (−15)] which is significantly greater than that of a conventional bulk typed SOA [1].

III. Conclusion

By using an external light-injected MQW SOA, we have demonstrated a 100-km optical fiber link that transports 77 channels of 64-QAM signals. Without external light pumping, the MQW SOA with a gain peak at 1310 nm had no input dynamic range at all; while with an external pumping laser at $\lambda_p = 1284$ nm and $P_{\text{pump}} = 8.8$ dBm, the saturation output power can be increased and the input dynamic range of an MQW SOA can be increased to 9 dB. We also found that the increase of SOA input dynamic range is due to the increase of $P_{\text{SAT},0.7\,\text{dB}}$, where $P_{\text{SAT},0.7\,\text{dB}}$ is the SOA output power of the 0.7-dB gain saturation point, whereas a successful transmission of multichannel 64-QAM transmission system requires the MQW SOA be operated below $P_{\text{SAT},0.7\,\text{dB}}$.

References

[1] P.-Y. Chiang, C. Tai, and W. I. Way, "33-channel 64-QAM signal transmission using a 1.3 μm semiconductor optical amplifier," *IEEE Photon Technol. Lett.*, vol. 8, pp. 119–121, 1996.

[2] C. Tai, P.-Y. Chiang, and W. I. Way, "Eight-way, 70-km transmission of 33-channel 64-QAM signals utilizing a 1.3 μm external modulation system and semiconductor optical amplifier," *IEEE Photon Technol. Lett.*, vol. 8, pp. 1246–1248, 1997.

[3] A. A. M. Saleh, R. M. Jopson, and T. E. Darcie, "Compensation of nonlinearity in semiconductor optical amplifiers," *Electron. Lett.*, vol. 24, pp. 950–952, 1988.

[4] J. A. Constable, I. H. White, A. N. Coles, and D. G. Cunningham, "Reduction of harmonic distortion and noise in a semiconductor optical amplifier using bias current feedback," *Electron. Lett.*, vol. 29, pp. 2042–2044, 1993.

[5] L. F. Tiemeijer, G. N. van den Hoven, P. J. A. Thijs, T. van Dongen, J. J. M. Binsma, and E. J. Jansen, "1310-nm DBR-type MQW gain-clamped semiconductor optical amplifiers with AM-CATV-grade linearity," *IEEE Photon Technol. Lett.*, vol. 8, pp. 1453–1455, 1996.

[6] M. Yoshino and K. Inoue, "Improvement of saturation output power in a semiconductor laser amplifier through pumping light injection," *IEEE Photon Technol. Lett.*, vol. 8, pp. 58–59, 1996.

[7] K.-P. Ho, S.-K. Liaw, and C. Lin, "Reduction of semiconductor laser amplifier induced distortion and crosstalk for WDM systems using light injection," *Electron Lett.*, vol. 32, pp. 2210–2211, 1996.

[8] R. J. Manning and D. A. O. Davies, "Three-wavelength device for all-optical signal processing," *Opt. Lett.*, vol. 19, pp. 889–891, 1994.

[9] C. Tai, S.-L. Tzeng, H.-C. Chang, and W. I. Way, "Reduction of saturation induced nonlinear distortion in MQW semiconductor optical amplifier using light injection and its application in multi-channel M-QAM signal transmission systems," in *Opt. Fiber Commun. Conf., Tech. Dig.*, San Jose, CA, 1998, paper ThO5.

[10] K. Maeda, M. Fuse, and K. Fujito, "Ultrahigh channel capacity optical CATV systems," in *Opt. Fiber Commun. Conf., Tech. Dig.*, San Jose, CA, 1996, paper WN3.