All-Optical Phase Modulation in a Traveling Wave Semiconductor Laser Amplifier

R. Hui, Q. Jiang, M. Kavehrad, and T. Makino

Abstract—**A novel all-optical phase modulation and wavelength conversion has been demonstrated in a traveling wave semiconductor laser amplifier. Even though the optical gain modulation caused by the saturation effect in a traveling wave semiconductor laser amplifier is sensitive to the signal wavelength, the optically controlled phase modulation is relatively independent of the signal wavelength.**

I. INTRODUCTION

OPTICAL wavelength conversion will be a key technique in the future optical communication and optical signal processing systems. Experiments of optical wavelength conversion have been reported by using the cross saturation effect in traveling wave semiconductor laser amplifiers (TWA) [1]–[4]. The signal bit rate as high as 10 GHz has been achieved in [4]. In these experiments, both the pump and the probe are injected into the TWA simultaneously. The intensity modulated pump light modulates the optical gain of the TWA and the CW probe at another wavelength is thus intensity modulated complementarily.

On the other hand, optical phase modulation in the lightwave systems are usually achieved by the guided wave electro-optic phase modulator on $LiNbO_3$. However, two important requirements seem hard to meet by this kind of phase modulator: optoelectronic integration with semiconductor lasers and all-optical controlling. Therefore, it is necessary to look for other solutions to meet the requirements of the future all-optical signal processing. Traveling wave semiconductor laser amplifier used as optical phase modulator has been reported when its injection current is electrically modulated [5], [6].

In this letter, we demonstrate a novel all-optical phase modulation and wavelength conversion using a TWA. Not only does it open the possibility for all-optical modulation format transformation, it is also useful in many applications, for example, the PSK modulation format will greatly increase the receiver sensitivity in a code division multiple (CDM) access local area network (LAN) [7].

II. EXPERIMENT AND DISCUSSION

The experimental setup is schematically illustrated in Fig. 1. A BT&D-SOA3100 TWA operating near 1300 nm was used in the experiment. The residual facet reflectivity of this device was estimated to be about 0.05% [8]. A DFB semiconductor laser emitting at 1309 nm was used to provide the pump light. A compact Nd:YAG laser with a narrow linewidth of 10 kHz emitting at 1319 nm wavelength was used as a probe, providing a continuous wave light. Another identical Nd:YAG laser was used as a local oscillator at the receiver side for the heterodyne detection of the amplified probe signal. The frequency difference between the two Nd:YAG lasers was stabilized with an automatic control system [9].

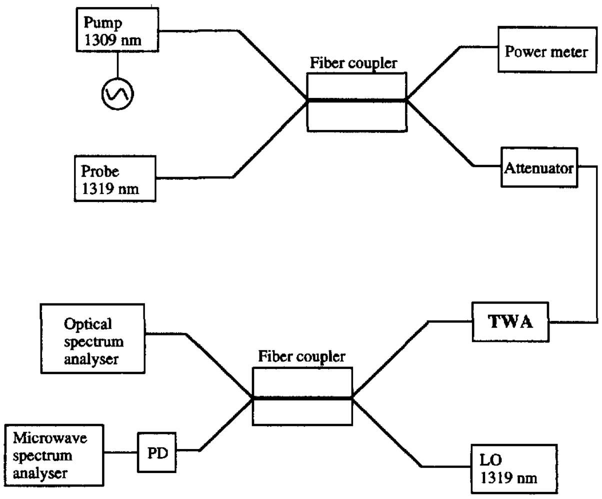

Fig. 1. Experimental setup.

First, the steady state performances of the TWA were characterized. The internal optical gain with and without a CW pump light injection is shown in Fig. 2 where the TWA is biased at 80 mA. This gain plot was obtained by measuring the ripples of the spontaneous emission spectrum caused by the residual facets reflectivity [10]. Without pump light, the gain peak is near 1290 nm. The injected pump light saturates the optical gain and shifts the gain peak toward the long wavelength side through the band-filling effect. To obtain this figure, the CW pump optical power was about −8.2 dBm in the input fiber to TWA. The optical gain variation caused by the injected pump light is shown by the triangles in Fig. 3. Because of the gain peak shift, the gain extinction shown in Fig. 3, decreases with wavelength logarithmically. It is important that the injected pump light not only saturates the optical gain, it introduces the refractive index variation as well through the gain/index coupling. The optical phase delay $\Delta\Phi$

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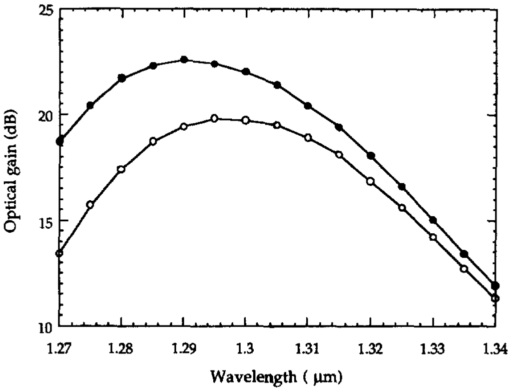


Fig. 2. Measured internal optical gain of the TWA biased at 80 mA. Solid points: no pump light injection. Open circles: with the pump optical power of −8.2 dBm at the input fiber of the TWA.

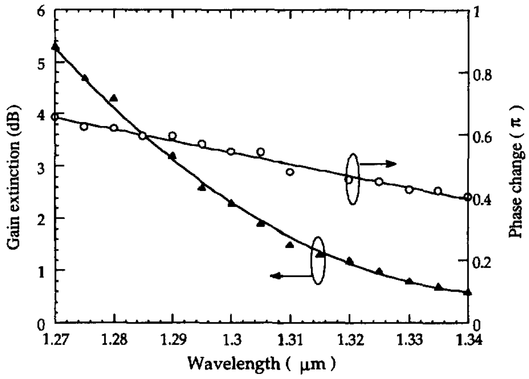


Fig. 3. Measured optical gain reduction (solid triangles) and phase change (open circles) caused by the injected CW pump optical of −8.2 dBm.

caused by this index variation has also been measured through the ripple wavelength shift $\Delta\lambda$ in the spontaneous emission spectra $\Delta\Phi = (2\pi n_0 L \Delta\lambda)/\lambda^2$, where $L = 0.45$ mm is the TWA device length, λ is the wavelength, and n_0 is the group index which can be evaluated from $n_0 = \lambda^2/(2L\delta\lambda)$ with $\delta\lambda$ being the period of the ripple. The measured probe phase delay $\Delta\Phi$ caused by the pump optical power is also displayed in Fig. 3 by open circles. It is interesting to note that the gain extinction ratio decreases rapidly with the wavelength, the phase modulation is quite insensitive to the wavelength. Therefore, even though the conventional AM/AM wavelength conversion may suffer from the poor extinction ratio when the signal is converted from short wavelength to long wavelength [1]–[4], a much more homogeneous conversion efficiency can be expected in the AM/PM wavelength conversion systems.

The physical reason behind this performance difference between gain and index modulation over the wavelength can be attributed to the inhomogeneous linewidth enhancement factor α as indicated in Fig. 4. The α factor of the TWA has been obtained through the measured gain and index changes and the α factor was defined as $(4\pi/\lambda)(\Delta n/\Delta g)$ being Δn the index change and Δg the corresponding change in the material gain. Higher values of α have been measured in the long wavelength side, this is comparable with the previously reported results [11]. It is worth noting that unlike the usual injection current modulation method [10], this optical modulation measurement is electrical parasitic free, especially, there is no thermal effect involved in this measurement.

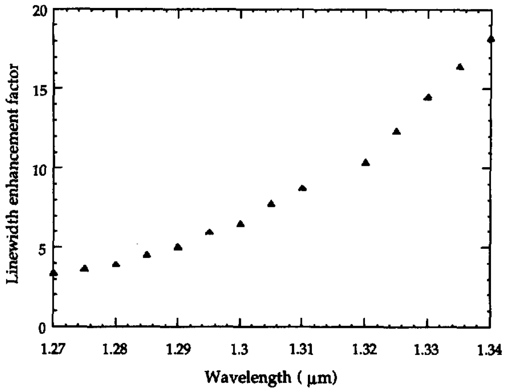


Fig. 4. Measured line width enhancement factor α of the TWA versus wavelength.

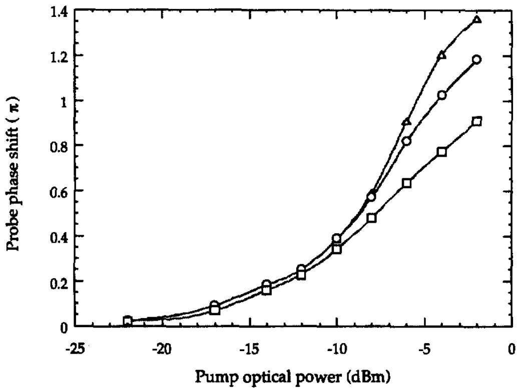
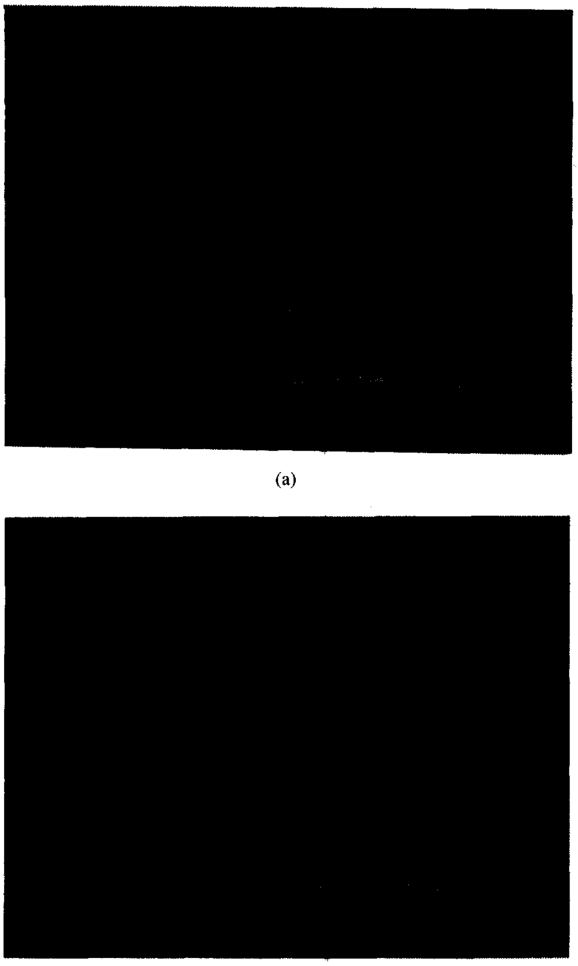


Fig. 5. Measured probe phase shift versus the injected pump optical power, with the probe and pump wavelengths at 1.319 μm and 1.309 μm, respectively, where the TWA is biased at 80 mA (triangles), 70 mA (circles), and 60 mA (rectangles).

Obviously, the pump induced phase shift in the TWA is directly proportional to the injected pump optical power. As an example, Fig. 5 shows the measured phase shift, at 1.3 μm wavelength, versus the input pump power for three different bias levels of the TWA, in this measurement, the wavelength of the pump laser is 1.309 μm. A −5 dBm pump optical power can introduce the phase variation around π, this pump power is achievable in the practical optical PSK applications.

Fig. 6(a) is the heterodyne spectrum obtained by the beating between amplified probe and the local oscillator when the pump light is not modulated. When the pump light laser was directly current modulated by a 300 MHz sinusoid wave, the carrier population in the TWA was modulated accordingly by the injected pump light, therefore both the optical gain and the refractive index were modulated at the same frequency. Thus an effective phase modulation was created on the amplified probe light. A clear evidence of the phase modulation on the


(a)

(b)

Fig. 6. Heterodyne spectra of the amplified probe light. (a) Pump laser is not modulated. (b) Pump laser is modulated by a 300 MHz sinusoid wave.

output probe wave is the decrease of the carrier component in the heterodyne spectrum as shown in Fig. 6(b), where the carrier component dropped to its minimum level. This indicates that the phase modulation index reaches approximately 2.405, and a carrier suppression ratio as high as 15 dB has been measured. The intensity difference of the two side bands in Fig. 6(b) is less than 1 dB, therefore, the effect of the residual AM modulation is negligible. This high phase modulation efficiency is thought to be the result of the relatively high linewidth enhancement factor which is about 10 at the probe wavelength of 1319 nm. Obviously, higher phase modulation efficiency can be expected with a TWA having a longer device length.

III. Conclusion

We have demonstrated a novel all-optical phase modulation and wavelength conversion in a traveling wave semiconductor laser amplifier. This functional application opens the possibility for all-optical controlling and wavelength conversion in the local area networks. Moreover, the possible optoelectronic integration with lasers on InP makes a TWA phase modulator a very promising component in the future optical communications networks.

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