Observation of WDM Crosstalk in Passive Semiconductor Waveguides

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***Abstract*—We show that passive InP–InGaAsP waveguides exhibit high nonlinear loss due to the highly energetic carriers generated by two-photon absorption. We have further demonstrated, for the first time, that due to this effect, severe crosstalk occurs between wavelength channels when they are transmitted through a semiconductor waveguide operated in the transparency region, at power levels used in typical wavelength-division-multiplexed (WDM) systems. Some solutions are proposed.**

***Index Terms*—Hot carrier absorption, optical crosstalk, passive semiconductor waveguides, two-photon absorption, WDM.**

I. Introduction

AS THE number of wavelength channels in wavelength division multiplexed systems keeps increasing, the total power guided through the waveguides of integrated devices may become considerably high. For active devices, it is well known that, due to gain compression, this can lead to signal distortion and interchannel crosstalk. However, until now, no report of such effects large enough to affect the bit-error rate (BER) of signals traversing passive waveguides of integrated semiconductor devices such as multiplexers, cross-connects, or multifrequency lasers has been made.

In the field of nonlinear optics, it is well known that two-photon absorption (TPA) in semiconductor media with a bandgap energy smaller than two times the photon energy poses a fundamental problem to all-optical switching and there exists no possibility for trading of device length against intensity in phase-shift-dependent devices [1]–[3]. In most optical switching experiments, very short pulses with high peak intensity ($\sim$10 W/μm^2) and yet low average power are employed, and in such a case the effect of TPA is clearly observed. On the other hand, in devices used in realistic wavelength-division-multiplexed (WDM) systems, the peak-intensities are much lower, and we do not expect any measurable effect occurring directly from TPA. However, in the TPA process, carriers with high energy (high temperature) are generated and, as will be shown, these hot carriers can have a significant effect on the transmission of typical WDM signals through optical waveguides operating in the transparency region below the bandgap.

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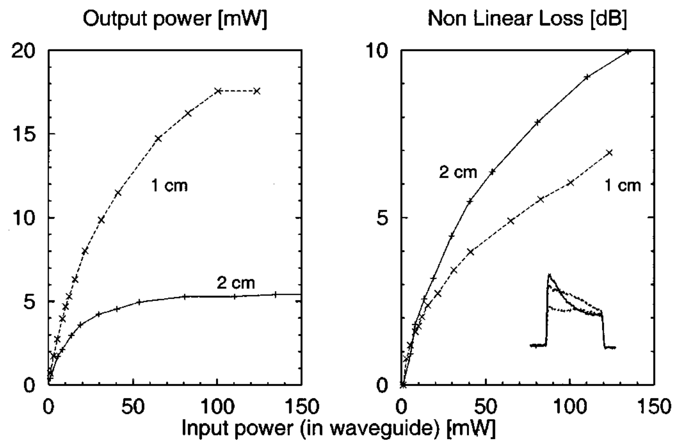

Fig. 1. Measured output power (left) and nonlinear loss (right) versus input power for a rib-loaded InP–InGaAsP passive waveguide ($W = 2.5\ \mu$m). The inset shows the transmission of a 4-ns square pulse for increasing input power ($P_{\rm in} =$ 10, 35, 70 mW).

II. Transmission Loss

Fig. 1 shows the results of a transmission experiment for an InP–InGaAsP waveguide with a rib-loaded slab structure (width 2.5 μm, rib thickness 90 nm, slab thickness 140 nm). Both the rib and the slab have a 1.30-μm bandgap while the transmitted light has a wavelength of 1553 nm, so the waveguide operates well into the transparency region. The results show that the transmission loss increases considerably with increasing input power and is much larger than the linear loss (2 dB/cm). Also, for a second type of waveguide, consisting of a single ridge embedded in an InP substrate (width 1.7 μm, height 260 nm), the maximum output power was limited to a value below 20 mW, although it was only 5 mm long. We first considered the TPA process to be responsible for the limiting effect. However the TPA coefficient as calculated from the slope of the inverse transmission $T^{-1}(T = P_{\rm out}/P_{\rm in})$ versus the incident power (see [1], [2]), for the results presented in Fig. 1, is approximately ten times as large ($\sim$500 cm/GW) as the value typically reported for InP–InGaAsP waveguides.

The inset of Fig. 1(b) shows the transmission of a square pulse with a length of 4 ns through the waveguide, showing that the loss increases across the pulse and with increasing pulse power. The fact that the loss increase is visible on this nanosecond timescale is again in contradiction with the TPA process since the effects of the latter are generally expected to be ultrafast [6]. Therefore, we believe that not the TPA process itself but the hot carriers that are generated by the process, and which can be involved in transitions that absorb photons with energy less than the bandgap, are responsible for the increasing loss. Since these

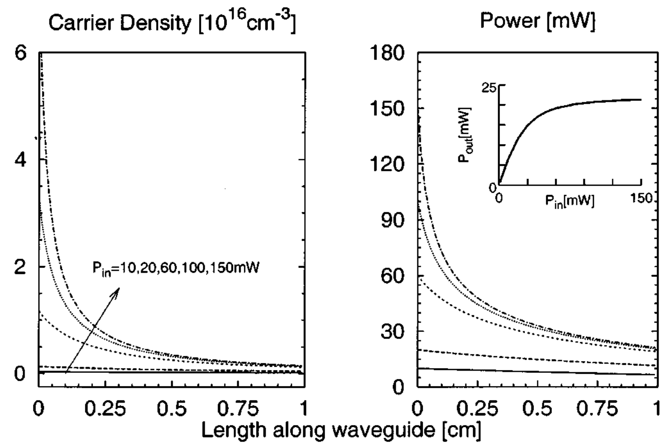

Fig. 2. Simulated carrier generation (left) and power evolution (right) along the waveguide ($\beta = 60$ GW/cm, $\tau_e = 4$ ns, $A_{\text{eff}} = 1.7\ \mu\text{m}^2$, $L = 1$ cm, $\alpha = 1.5$ dB/cm). Inset of right picture shows the output power as function of the input power.

carriers can only recombine by spontaneous emission or nonradiative processes and have a lifetime in the range 1∼5 ns, during the pulse the amount of carriers generated by the TPA-process keeps increasing until an equilibrium is reached. The carrier rate equation for the waveguide is given by

$$\frac{dN(z)}{dt} = \frac{1}{h\nu}\frac{\beta}{2}I^2(z) - \frac{N(z)}{\tau_e} \quad (1)$$

with N the carrier density, I the intensity, and τ_e the carrier recombination time. The highly energetic carriers generated by TPA in both the conduction and valence bands can give up their excess energy through carrier–carrier scattering and heat the rest of the distribution. The distribution will subsequently cool back to the lattice temperature via phonon emission with a time constant of 1 ps (although in some cases where very hot carriers were involved, time constants up to almost 3 ps were measured [8]). Since these time constants are much smaller than the carrier recombination time τ_e, we may consider a carrier distribution with an equilibrium temperature and there is no need to add an additional term describing the carrier thermalization process in (1). The intensity evolution along the waveguide is given by

$$\frac{dI}{dz} = -\alpha I - \beta I^2 - \sigma N(z) I \quad (2)$$

where a term is added to account for the free carrier induced loss. For continuous-wave (CW) power injection, (1) and (2) can be readily solved to give us the evolution of the intensity and the carrier density along the waveguide. As shown in Fig. 2(a), the amount of generated carriers is relatively small (order $0.1 - 8 \times 10^{16}\ \text{cm}^{-3}$). Typical values for cool free-carrier absorption in InGaAsP are around 1 dB/cm for a carrier density of 10^{16} cm^{-3} [7]. Therefore, at first sight the much higher experimentally observed loss cannot be explained by carrier accumulation. However, the generated carriers have a high energy and as noted in [4] and [5], this can increase the absorption in the waveguide considerably. Fig. 2(b) shows the evolution of the power along the waveguide, taking into account the hot carrier absorption cross section σ reported in [5], $\sigma = 2 \times 10^{-16}$ cm^2, (or $\alpha = 8.7$ dB/cm for $N = 10^{16}$ cm^{-3}). This figure shows that the loss is mainly important in the first few millimeters of the waveguide and from the inset, showing the power at the output of the waveguide, the limiting effect is clearly visible. Similar experiments were performed using silicon waveguides (an indirect bandgap material); however, up to an input power of 300 mW, no nonlinear loss was observed.

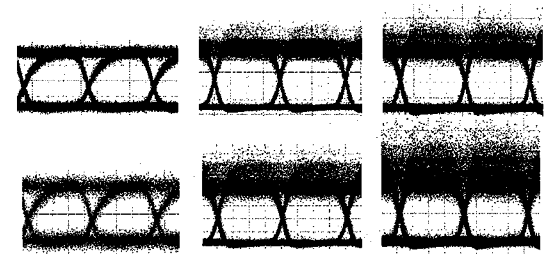

Fig. 3. Eye diagrams (2.5 Gb/s) measured from the output of a 1.2-μm-wide buried ridge waveguide. Upper row: single channel in waveguide. Lower row: two channels present in waveguide. The second channel is filtered out using a bandpass filter before measuring the eye diagram. Left to right: $P_{\text{in, total}} = 1$ mW, 75 mW, 150 mW.

III. Interchannel Crosstalk

Since the limiting effect is a function of the total input power, it may cause crosstalk between several wavelength channels of a WDM-signal traversing the optical waveguide. To verify this, we measured the BER as a function of the input power for a two-channel system. Two laser beams, ($\lambda_1 = 1553$ nm and $\lambda_2 = 1565$ nm) were combined using a 3-dB coupler and subsequently modulated with a 2.488-Gb/s nonreturn-to-zero pseudorandom bit sequence (NRZ-PRBS) signal of length 2^{31-1}, using a lithium–niobate Mach–Zehnder modulator. Next, the two signals were decorrelated using an optical fiber with a total dispersion of $DL = 130$ ps/nm, amplified using a high-power erbium-doped fiber amplifier and coupled into the waveguide. At the output, the $\lambda_1 = 1553$ nm signal was selected using a bandpass filter with a 0.3-nm full-width at half-maximum (FWHM).

Fig. 3 shows eye diagrams measured from the output of the bandpass filter, for increasing input power and with and without the second channel present. From the upper row (only one channel active), we see that the thickness of the on-level increases considerably with increasing input power, indicating that—as expected from the previously described experiments—the loss experienced by a particular bit depends on the value of the preceding bits. Furthermore, the lower row shows that the “1” thickness further increases when the second signal is added. BER measurements were performed using an avalanche photodiode with clock recovery and decision circuit as the receiver. Fig. 4 shows, respectively, the results for a rib-loaded slab waveguide ($W = 2.5\ \mu$m, $L = 1$ cm) and a buried ridge waveguide ($W = 1.2\ \mu$m, $L = 5$ mm). For the first waveguide, small penalties are visible for average input powers below 75 mW (penalty of 0.5 dB and 1.0 dB, respectively, for $P_{\text{in}} = 50$ mW and 75 mW at $\text{BER} = 10^{-9}$—the denoted powers are the total averaged power coupled into the waveguides). For larger input powers, penalties up to 2 (5) dB were measured for $P_{\text{in}} = 100$ (150) mW. For the buried ridge waveguide, although shorter in length, the effect was even more severe, which can be attributed to the smaller effective cross

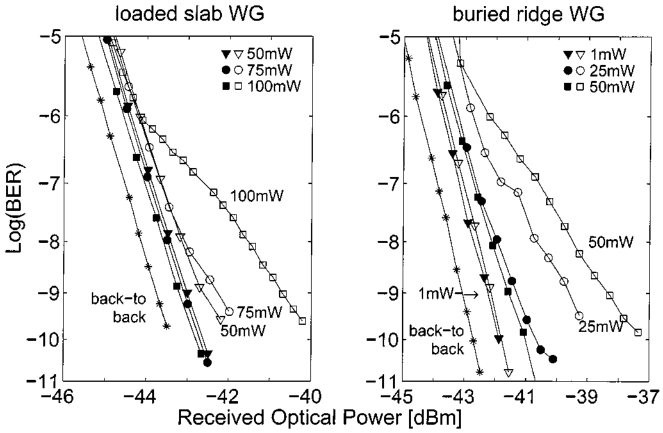

Fig. 4. BER measurements for a rib-loaded (left) and a buried ridge waveguide (right). Closed (open) symbols are for single- (two-) channel operation. The denoted powers are the total power coupled into the waveguide (sum of both channels).

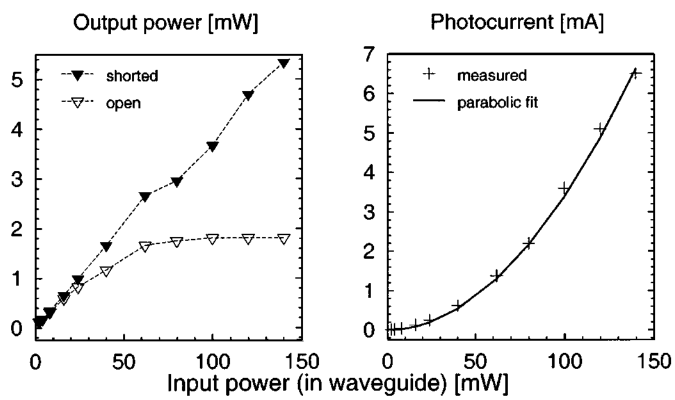

Fig. 5. Transmission results (left) and generated photocurrent (right) for a buried ridge waveguide with a p-n junction ($\lambda_g = 1.3\ \mu$m).

section compared to the slab-loaded waveguide. In this case, there is a small penalty even when no second channel is added, and for total powers as low as 25 mW, a penalty over 2 dB was observed (at $\mathrm{BER} = 10^{-9}$) when a second channel was added.

The generated carriers can be removed by introducing a p-n junction in the waveguide and shorting the contacts. We investigated this using a 1.3-μm semiconductor optical amplifier and the results shown in Fig. 5 indicate clearly that the nonlinear loss is indeed considerably decreased. Applying a reverse bias voltage did not further improve the transmitted power. The almost perfect parabolic fit for the photocurrent [Fig. 5(b)] demonstrates that the carriers are mainly generated by the TPA-process and not by linear absorption. A drawback of the p-n junction is the increase in linear loss due to the necessary doping of the cladding layers. Another possibility for carrier removal is to shorten the carrier lifetime by a proton bombardment, creating defects for carrier recombination and thereby minimizing the accumulation of photogenerated carriers. In [8] this was shown to slightly enhance the efficiency of the four-wave mixing effect, and although it also increases the linear loss somewhat, the same procedure can be applied to diminish the interchannel crosstalk.

IV. Conclusion

We have shown, for the first time, that severe crosstalk may occur between wavelength channels when they are transmitted through a semiconductor waveguide operated in the transparency region below the bandgap. The crosstalk originates from a power-dependent loss induced by carriers generated by two-photon absorption. Since this happens at power levels that are very likely to occur in realistic devices for WDM networks, this crosstalk phenomenon has to be taken into account when designing these devices. Typical examples of waveguides where this is important are the common entry ports of multiplexers/demultiplexers, cross-connects or multifrequency lasers. Furthermore, the loss induced by the photogenerated carriers may limit the output power of high-power lasers having a passive waveguide section, such as widely tunable lasers. BER measurements suggest that it is important to keep the effective area of the waveguides shared by multiple wavelengths as large as possible. Other remedies include collecting the carriers in a shorted p-n junction or defect generation via proton bombardment. Note that the process is slow and so it is ineffective for all optical switching or optical limiting.

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References

[1] V. Mizrahi, K. W. Delong, and G. I. Stegeman, "Two-photon absorption as a limitation to all-optical switching," *Opt. Lett.*, vol. 14, pp. 1140–1142, Oct. 1989.

[2] A. Villeneuve, M. Sundheimer, N. Finlayson, G. I. Stegeman, S. Morasca, C. Rigo, R. Calvani, and C. De Bernardi, "Two-photon absorption in InGaAlAs/InP waveguides at communication wavelengths," *Appl. Phys. Lett.*, vol. 56, pp. 1865–1867, May 1995.

[3] H. K. Tsang, R. V. Penty, I. H. White, R. S. Grant, W. Sibbett, J. B. D. Soole, H. P. LeBlanc, N. C. Andreadakis, R. Bhat, and M. A. Koza, "Two-photon absorption and self-phase modulation in InGaAsP/InP multi-quantum-well waveguides," *J. Appl. Phys. Lett.*, vol. 70, pp. 3992–3994, Oct. 1991.

[4] J. Mork, J. Mark, and C. P. Seltzer, "Carrier heating in InGaAsP laser amplifiers due to two-photon absorption," *Appl. Phys. Lett.*, vol. 64, pp. 2206–2208, Apr. 1994.

[5] H. K. Tsang, P. A. Snow, I. E. Day, I. H. White, R. V. Penty, R. S. Grant, Z. Su, G. T. Kennedy, and W. Sibbett, "All-optical modulation with ultrafast recovery at low pump energies in passive InGaAs/InGaAsP multiquantum well waveguides," *Appl. Phys. Lett.*, vol. 62, pp. 1451–1453, Mar. 1993.

[6] K. L. Hall, G. Lenz, A. M. Darwish, and E. P. Ippen, "Subpicosecond gain and index nonlinearities in InGaAsP diode lasers," *Opt. Commun.*, vol. 111, pp. 589–612, Oct. 1994.

[7] E. J. Murphy, *Integrated Optical Circuits and Components*. New York: Marcel Dekker, 1999.

[8] M. Joschko, P. Langlois, E. R. Thoen, E. M. Koontz, E. P. Ippen, and L. A. Kolodziejski, "Ultrafast hot-carrier dynamics in semiconductor saturable absorber mirrors," *Appl. Phys. Lett.*, vol. 76, pp. 1383–1385, Mar. 2000.

[9] E. R. Thoen, J. P. Donnelly, S. H. Groves, K. L. Hall, and E. P. Ippen, "Proton bombardment for enhanced four-wave mixing in InGaAsP–InP waveguides," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 311–313, Mar. 2000.