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Light slow-down in semiconductor waveguides due to population pulsations

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There is currently a large interest in applying fundamental discoveries on slow light for practical applications, e.g. buffering and storage of light [1]. While the first demonstrations of light slow-down were performed in ultra-cold atomic gasses using the physical effect of electromagnetically-induced transparency, recent experiments were performed in a ruby crystal at room temperature [2], based on the effect of coherent population oscillations (CPO). In this paper we analyze theoretically the prospect of inducing light-slow down in a semiconductor waveguide based on CPO and present experimental observations of the effect.

Fig. 1 (top) shows numerical calculations of the effective group refractive index, n_g, experienced by a probe beam in the presence of a pump for an absorbing semiconductor medium. Due to wave-mixing mediated by carrier-density pulsations, the probe experiences strong dispersion, which leads to the shown detuning-dependence of n_g. The result depends on the gain-index coupling (α-parameter), except for zero detuning, where the result can be simply interpreted in terms of absorption saturation. The negative values for the group index correspond to superluminal propagation and were also obtained in Ruby [2]. Fig. 1 (bottom) shows n_g averaged over the length of a 100 μm waveguide, when propagation effects are included. Due to absorption saturation, the induced change of n_g depends nonlinearly on the input intensity, P_{in}.

Experimentally, the group index change induced in a reverse-biased semiconductor waveguide (L=100 μm) is measured by employing a sideband modulation technique [2]. The temporal delay, Δt, is measured relative to a frequency reference by using a network analyzer and is converted to a group index change, $\Delta n_g = c\ \Delta t/L$. Fig. 2 shows the measured Δn_g values as function of reverse bias and input power. As the reverse bias is increased, the absorption of the waveguide increases and at the same time, due to carrier sweep-out, the carrier lifetime is reduced, reaching a value as low as 10 ps for 3 V reverse bias. The induced index change depends strongly on the lifetime, as documented in Fig. 1 (bottom), which shows the effect of lowering the lifetime from 200 ps (as used in Fig. 1, top) to 20 ps. The relatively small measured Δn_g is thus well explained by the short lifetime, which, on the other hand, implies a bandwidth of several GHz, to be compared to the kHz range in [2]. Furthermore, the experimental observation of an optimum reverse voltage can be explained by the reverse bias dependence of the lifetime.

The scaling of the group index change with carrier lifetime has important consequences for the applications and will be further discussed at the conference.

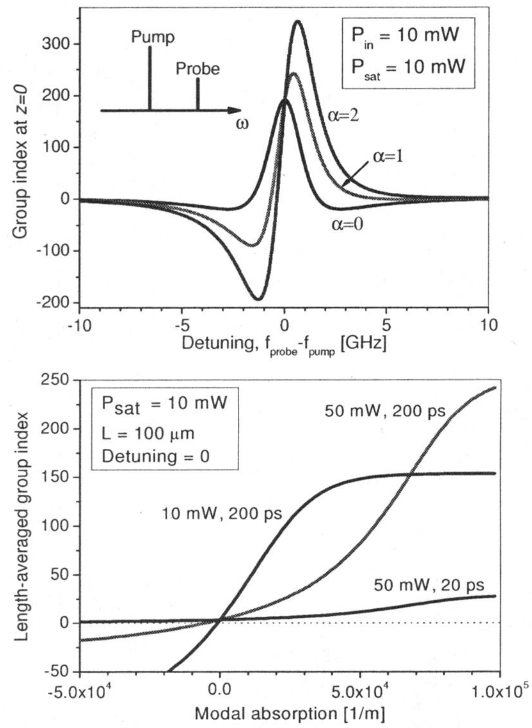

Fig. 1. Calculated variation of group index with detuning (top; at waveguide input for an absorption coefficient of $5 \cdot 10^4\ m^{-1}$) and modal absorption (bottom; averaged over waveguide length).

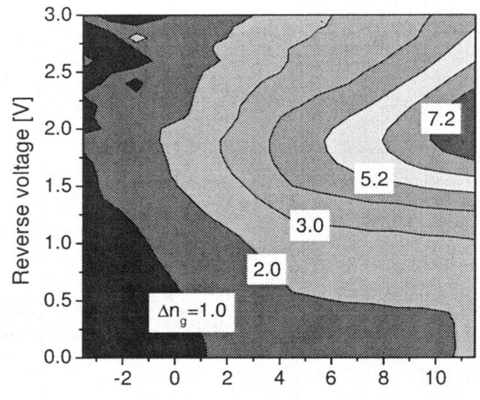

Fig. 2. Contour plot of measured change in group index versus input intensity and reverse voltage for a 100 μm long semiconductor waveguide.

[1] C. J. Chang-Hasnain et al., Proc. IEEE, vol. 91, pp. 1884-1897 (2003).

[2] M. Bigelow et al., Science, vol. 301, pp. 200-202 (2003).