Theoretical calculations of the carrier induced refractive index change in tensile-strained InGaAsP for use in 1550 nm semiconductor optical amplifiers

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Nonlinear polarization rotation (NPR) in semiconductor optical amplifiers (SOAs) has applications in all-optical signal processing. Modeling NPR in a SOA requires knowledge of the carrier density induced refractive index change. The tensile-strained bulk SOA has attracted much interest due to its relative ease of fabrication and commercial devices are now available. In this letter we determine the polarization dependent refractive index change in such a SOA, with an InGaAsP active region, operating in the 1550 nm region and investigate its dependence on carrier density and wavelength. © 2008 American Institute of Physics. [DOI: 10.1063/1.3021393]

There has been considerable progress in the exploitation of optical nonlinearities in semiconductor optical amplifiers (SOAs). Much attention has been paid to carrier density induced nonlinearities, which lead to nonlinear polarization rotation (NPR) in SOAs.1–3 NPR in a SOA is a mixture of cross-phase and cross-gain-modulation effects that cause a rotation of a probe signal polarization in the presence of pump light. The tensile-strained bulk SOA, with a rectangular cross-section active region, has attracted much interest due to its ease of fabrication.4,5 Due to the rectangular cross section the transverse electric (TE) mode optical confinement factor can be significantly larger than that of the transverse magnetic (TM) mode. The introduction of tensile train in the active region can be used to increase the TM material gain coefficient relative to the TE material gain coefficient to compensate for the different confinement factors. Commercial tensile-strained devices, operating in the 1550 nm region, have an InGaAsP active region tensile strained by a lattice mismatch with the surrounding InP layers. NPR in a SOA is fundamentally due to the carrier density dependence of the TE and TM mode active region refractive indices, caused by band filling (BF) and free-carrier absorption (FCA).6 Most research on NPR in SOAs has assumed that the refractive index change is polarization independent and that its derivative with respect to carrier density is constant. As this letter demonstrates, polarization independence can only be assumed in unstrained material and the derivative with respect to carrier density is strain, wavelength, and carrier density dependent. The inclusion of this dependency should improve the accuracy of models used to predict NPR in SOAs. In this letter we determine the carrier density induced refractive index change in typical tensile-strained bulk InGaAsP used in a practical SOA (Ref. 6) and examine its dependence on wavelength, carrier density, and strain. The carrier density \( n \) induced polarization dependent refractive index change in a semiconductor material at photon energy \( E \) due to BF and FCA can be expressed as

\[
\Delta N_{\text{TE,TM}}(E,n) = \Delta N_{\text{BF,TE,TM}}(E,n) + \Delta N_{\text{FCA}}(E,n),
\]

(1)

The refractive index change due to BF is given by the Kramers–Kronig relationship,\(^6\)

\[
\Delta N_{\text{BF,TE,TM}}(E,n) = \frac{2c\hbar}{e^2} \text{PV} \int_0^\infty \frac{\alpha_{\text{TE,TM}}(E',n) - \alpha_{\text{TE,TM}}(E',0)}{E'^2 - E^2} dE',
\]

where PV is the principal value of the integral and the material absorption \( \alpha_{\text{TE,TM}}(E,n) \) is determined using the band structure and material gain model\(^7\) and the material parameters.\(^5\) The TE and TM gain peak wavelengths for this SOA with a strain of 0.15% and a carrier density of \( 3 \times 10^{24} \) m\(^{-3} \) are approximately 1540 nm. \( \alpha_{\text{TE,TM}} \) is given by

![FIG. 1. (Color online) Typical TE (solid lines) and TM absorption (dashed lines) spectra. The strain is 0.15%. The carrier density increases from \( 1 \times 10^{13} \) to \( 4 \times 10^{24} \) m\(^{-3} \) in increments of \( 1 \times 10^{14} \) m\(^{-3} \).](https://example.com/fig1.png)
\[
\alpha_{\text{TE,TM}}(E,n) = \frac{C_g}{E} \sum_{b=LH,HH,SO} \int_0^\infty \int_0^\pi k^2 \sin \theta |M_{\text{TE,TM},b}(k,\theta)|^2 \\
\times L[E_{cc,b}(k,\theta)][1-f_c(k)]_f_{cc}(k,\theta)d\theta dk,
\]
where “LH,” “HH,” and “SO” denote the light-hole, heavy-hole, and split-off valence bands (VBs) respectively, \( C_g = e^2/2\pi \varepsilon_0 mc_0^2 N_r \), \( N_r \) is the refractive index with no injected carriers, \( M_{\text{TE,TM},b}(k,\theta) \) are the matrix elements, and \( E_{cc,b}(k,\theta) \) are the conduction band (CB) to VB transition energies. \( k \) and \( \theta \) are the magnitude and azimuth of the momentum vector. Intraband relaxation and doping effects are taken into account using a sech line broadening function \( L(E_{cc,b}) = \tau_r/\hbar \pi \text{sech}[\tau_r/\hbar(E_{cc,b} - \hbar\omega)] \), where \( \tau_r \) the effective intraband relaxation time is taken to be 22.4 fs. The absorption spectrum calculations take into account band-gap shrinkage. Calculated absorption spectra for a strain of 0.15% are shown in Fig. 1. Using Eq. (2) \( \Delta N_{\text{BF,TE,TM}} \) can be

FIG. 2. (Color online) FCA induced refractive index change at 1550 nm for a strain of 0.15%. The parabolic approximation uses effective masses for unstrained InGaAsP.

FIG. 3. (Color online) BF and FCA contributions to the refractive index change at 1550 nm as a function of carrier density. The strain varies from 0% to 0.2% in increments of 0.05%.

FIG. 4. (Color online) BF and FCA contributions to the refractive index change vs wavelength for no strain. The carrier density increases from \( 1 \times 10^{24} \) to \( 4 \times 10^{24} \) m\(^{-3} \) in increments of \( 1 \times 10^{24} \) m\(^{-3} \) in the direction of the arrows. There is no polarization dependence.

FIG. 5. (Color online) BF and FCA contributions to the refractive index change as a function of wavelength, with the carrier density as parameter, for a tensile strain of 0.15%. The carrier density increases from \( 1 \times 10^{24} \) to \( 4 \times 10^{24} \) m\(^{-3} \) in increments of \( 1 \times 10^{24} \) m\(^{-3} \) in the direction of the arrows. The solid and dotted lines of the BF contribution refer to TE and TM polarizations, respectively.
determined as a function of wavelength, carrier density, and strain. The refractive index change due to FCA is usually given as

\[ \Delta N_{\text{FCA}}(E,n) = -\frac{e^2 \hbar^2}{2N_e \varepsilon_0 E^2} \left( \frac{n}{m_c} + \frac{p}{m_v} \right), \tag{4} \]

where parabolic bands are assumed. \( m_c \) and \( m_v \) are the effective masses of the CB and VB (heavy-hole), respectively. \( p \) is the VB hole density. In general, the CB can deviate from being parabolic. Furthermore in tensile-strained material, the light-hole band is raised above the heavy-hole band and can contribute significantly to the FCA refractive index change. The VB effective masses are not constant but can vary significantly with momentum. Generalizing from Eq. (4), the CB contribution to \( \Delta N_{\text{FCA}} \) is given by

\[ \Delta N_{\text{FCA},c}(E,n) = -\frac{e^2 \hbar^2}{2N_e \varepsilon_0 E^2} \int_0^\infty \frac{k^2}{\pi^2 m_c(k)} f_c(E_c(k)) dk, \tag{5} \]

where \( E_c \) is the CB energy-momentum relationship. \( m_c(k) \) is the \( k \)-dependent effective mass obtained using a parabolic fit to \( E_c(k) \) in a small region around \( k \). \( k^2/\pi^2 m_c(k) \) is the density of states and \( f_c \) is the Fermi–Dirac distribution function. Similarly the VB contribution to \( \Delta N_{\text{FCA}} \) is given by

\[ \Delta N_{\text{FCA},v}(E,n) = -\frac{e^2 \hbar^2}{2N_e \varepsilon_0 E^2} \sum_{b=HH,LL} \int_0^\infty dk \int_0^{\pi} \frac{k^2 \sin \theta}{2\pi^2 m_v(k,\theta)} \]

\[ \times f_v[E_v,b(k,\theta)] d\theta. \tag{6} \]

It is assumed that \( p=n \), as is usually the case in SOAs. \( E_v,b(k,\theta) \) is the VB energy-momentum relationship and \( m_v(k,\theta) \) is the \( k \) and \( \theta \) dependent effective mass obtained using a parabolic fit to \( E_v,b(k,\theta) \) in a small region around \( k \) for a given \( \theta \). Equation (4) can be rewritten as

\[ \Delta N_{\text{FCA}}(E,n) = \Delta N_{\text{FCA},c}(E,n) + \Delta N_{\text{FCA},v}(E,n). \tag{7} \]

A typical carrier density dependence of \( \Delta N_{\text{FCA}} \) showing the CB and VB contributions and comparison with the parabolic approximation is shown in Fig. 2. The BF and FCA contributions to the refractive index change at 1550 nm are shown in Fig. 3 as a function of carrier density with strain as parameter. The FCA component is effectively independent of the strain. However, the BF contribution does have significant polarization dependence. The BF and FCA contributions to the refractive index change as a function of wavelength, with the carrier density as parameter for strains of 0% and 0.15%, are shown in Figs. 4 and 5, respectively. The refractive index change has a significant wavelength dependency and when strain is present significant polarization dependency.