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Universal method to determine the thermo-optic coefficient of optical waveguide layer materials using a dual slab waveguide

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A dual slab waveguide device method for determining the thermo-optic coefficient of waveguide layer materials is demonstrated. Temperature change-induced optical path length imbalance between two single slab waveguide modes provides the primary mechanism for detection. The waveguide mode output field phase change differences are encoded in shifts in the far field interference pattern. To illustrate the method, the thermo-optic coefficients of two $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ quaternary alloys, 1.3$Q$ and 1.15$Q$, are measured at a wavelength of 1.55 $\mu$m and at a center temperature of 25.2 °C. Their ratio is in excellent agreement with previous work, in accordance with optical dispersion models. © 2007 American Institute of Physics. [DOI: 10.1063/1.2795340]

An understanding of the thermal behavior of guided wave photonic devices is crucial; whether one is designing a device where this behavior provides the device functionality or whether it is a problem to be managed. The intrinsic thermal response of a device (as opposed to extrinsic sources due to the packaging) can be modeled accurately provided that the thermo-optic coefficients of the materials comprising the device are known. For many common optical materials such as silica lithium niobate, silicon, and other semiconductor crystals such as the III-V binaries (InP, GaAs, etc.), these coefficients are now described well by the pioneering dispersion model of Ghosh. Experimental verification of thermo-optic coefficients, however, requires suitable sample geometries such as a prism or etalon or integrated optical waveguide device, and in part for this reason, there is a scarcity (essentially an absence) of the reported thermo-optic coefficients of materials of the quaternary III-V compound semiconductors. These alloys are not formed as bulk crystals but as thin epitaxial layers by metal organic vapor phase epitaxy (MOVPE) growth on the binary alloy crystal wafer substrate. Despite the obviously successful development of vital optoelectronic components (for example, diode lasers and photodetectors) that use quaternary materials, designers would benefit from having access to such data and we provide here a device-based method that is relatively simple to implement that allows the measurement, in principle, of any desired III-V alloy system across wide ranges of temperatures and wavelengths. We report the thermo-optic coefficient for two InGaAsP compositions at the wavelength center of the ITU C band $\lambda_0=1.55$ $\mu$m and at a center temperature of 25.2 °C.

We previously demonstrated an InP/InGaAsP dual slab waveguide unbalanced interferometer designed to detect picometer level changes in $C$-band laser wavelength. The interferometer consists very simply of five epitaxial layers of alternately low and high refractive indices (here, InP and InGaAsP, respectively) fabricated on suitable absorbing layers and on a heavily doped InP substrate (see Table I and the inset of Fig. 1). End fire of an oversized optical field into the waveguide sample excites both single slab modes with equal efficiency. All nonguided light is either absorbed into the lower layers or scattered through the device surface. At the device output, the two modes diffract into the far field at the output plane where they form a clear interference pattern analogous to Young’s fringes (Fig. 1). The spatial intensity distribution of the fringe pattern provides information on the relative phase difference, between the “upper” ($u$) and “lower” ($l$) waveguide fields at the output plane of the device, reflecting the difference in effective refractive index, $N_{ul}(T)$ between the modes. Thickness and compositional differences between the two guiding layers produce a difference in the effective thermo-optic coefficient $dN_{ul}/dT$ of the two modes. As the temperature changes $\Delta T$, the net effect is an output phase change difference $\Delta \Phi$ related to the effective index change between the modes and change in sample length due to thermal expansion given by

$$\Delta \Phi = \frac{2\pi}{\lambda_0} L \Delta T [dN_u/dT - dN_l/dT + \alpha(N_u - N_l)] + \alpha \Delta T (dN_u/dT - dN_l/dT)],$$

(1)

where $L$ is the length of the interferometer chip and $\alpha$ is the

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Dopant</th>
<th>Thickness ($\mu$m)</th>
<th>$n$ (1.55 $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>2 in. InP VCz</td>
<td>S</td>
<td>350</td>
<td>⋯</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>Si</td>
<td>0.5</td>
<td>⋯</td>
</tr>
<tr>
<td>2</td>
<td>InGaAs</td>
<td>⋯</td>
<td>1.0</td>
<td>⋯</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>⋯</td>
<td>1.5</td>
<td>3.1836</td>
</tr>
<tr>
<td>4</td>
<td>1.3Q InGaAsP</td>
<td>⋯</td>
<td>0.5</td>
<td>3.3907(8)</td>
</tr>
<tr>
<td>5</td>
<td>InP</td>
<td>⋯</td>
<td>2.3</td>
<td>3.1836</td>
</tr>
<tr>
<td>6a</td>
<td>1.3Q InGaAsP</td>
<td>⋯</td>
<td>0.2</td>
<td>3.3907(8)</td>
</tr>
<tr>
<td>6b</td>
<td>1.15Q InGaAsP</td>
<td>⋯</td>
<td>0.3</td>
<td>3.3206(4)</td>
</tr>
<tr>
<td>7</td>
<td>InP</td>
<td>⋯</td>
<td>2.0</td>
<td>3.1836</td>
</tr>
</tbody>
</table>

TABLE I. Device layer structure with alternative layer 6 for the 1.3Q (a) and 1.15Q (b) designs. The measured photoluminescence wavelengths ($\lambda_g$) of the ternary and quaternary materials are given in parentheses.

Electronic mail: g.h.cross@durham.ac.uk
The effective thermo-optic coefficient can be simplified to
\[ \frac{dN_w}{dT} = 2 \frac{\partial N_w}{\partial n_{\text{tap}}} \frac{dn_{\text{tap}}}{dT} + \frac{\partial N_w}{\partial n_{\text{Q}}} \frac{dn_{\text{Q}}}{dT}, \]
where \(dn_{\text{Q}}/dT\) is the thermo-optic coefficient of the quaternary waveguide layer material. Using this definition in Eq. (1) leads to
\[ \frac{\partial N_w}{\partial n_{\text{Q}}} \frac{dn_{\text{Q}}}{dT} = -2 \frac{\partial N_w}{\partial n_{\text{tap}}} \frac{dn_{\text{tap}}}{dT} - \alpha(N_w - N_l). \]

For an interferometer where the quaternary alloy is identical in upper and lower slab waveguides, we have
\[ \frac{dn_{1.3Q}}{dT} = \left[ \frac{\lambda_0 \Delta \Phi}{2 \pi L \Delta T} - 2 \frac{\partial N_u}{\partial n_{\text{tap}}} - 2 \frac{\partial N_l}{\partial n_{\text{Q}}} \right] \frac{dn_{\text{tap}}}{dT} \]
and a rearrangement of Eq. (3) provides a similar equation for the dual quaternary system [structure (b)] where the unknown (1.15Q) quaternary material is in the upper waveguide,
\[ \frac{dn_{1.15Q}}{dT} = \left[ \frac{\lambda_0 \Delta \Phi}{2 \pi L \Delta T} - 2 \frac{\partial N_u}{\partial n_{\text{tap}}} - 2 \frac{\partial N_l}{\partial n_{\text{Q}}} \right] \frac{dn_{\text{tap}}}{dT} - \alpha(N_u - N_l) \]
Thus, we can determine the thermo-optic coefficient for the quaternary materials from the measured phase changes provided that we have a reliable value for the thermo-optic coefficient of InP. An acceptable value, \(dn_{\text{tap}}/dT = (1.95 \pm 0.05) \times 10^{-4} \text{ K}^{-1}\), was taken from the average results of a range of published experimental measurements carried out at or near 1.55 \(\mu\text{m}\) and at 25 °C.

Two structures were fabricated using 1.3Q material for both guiding layers in one design (a) and guiding layers of each of 1.3Q and 1.15Q materials in the other (b) (Table I). The experimentally determined photoluminescence wavelength were taken to indicate the position of the band gap for the quaternary materials, and refractive index values for these layers at 1550 nm were obtained using the formulas of Adachi,\(^{11}\) built into the FIMMWAVE® program of Photon Design.\(^{12}\) The calculated values of \(\partial N_w/\partial n_{\text{tap}}\) and \(\partial N_w/\partial n_{\text{Q}}\) are given in Table II.

Devices were cleaved into a length of 12 mm and a width of 2 mm. The interferometer chip was clamped within a dual-stage temperature-controlled housing with Peltier control to better than ±5 mK for the sample. The input light was provided by an Agilent 81640A tuneable laser source coupled into a standard single mode optical fiber wound onto a polarization controller allowing both transverse electric (TE) and transverse magnetic (TM) polarized excitations of the modes.

The cleaved bare fiber output facet was positioned near to the interferometer end face in order for the light to diffract to a beam size sufficient to excite both waveguiding modes with approximately equal efficiency. In order to prevent uncoupled and scattered light from reaching the detect-
TABLE II. Calculated rate of change of effective mode index with layer index for 1.3Q [structure (a)] and 1.3Q/1.15Q [structure (b)] devices.

<table>
<thead>
<tr>
<th>Structure (a)</th>
<th>TE</th>
<th>TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial N_e}{\partial n_{Qa}}$</td>
<td>0.3264</td>
<td>0.2550</td>
</tr>
<tr>
<td>$\frac{\partial N_l}{\partial n_{Qa}}$</td>
<td>0.7678</td>
<td>0.7136</td>
</tr>
<tr>
<td>$\frac{2\partial N_e}{\partial \lambda_{ap}}$</td>
<td>0.6820</td>
<td>0.7544</td>
</tr>
<tr>
<td>$\frac{2\partial N_l}{\partial \lambda_{ap}}$</td>
<td>0.2456</td>
<td>0.3027</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structure (b)</th>
<th>TE</th>
<th>TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial N_e}{\partial n_{Qb}}$</td>
<td>0.4121</td>
<td>0.3586</td>
</tr>
<tr>
<td>$\frac{\partial N_l}{\partial n_{Qb}}$</td>
<td>0.7678</td>
<td>0.7137</td>
</tr>
<tr>
<td>$\frac{2\partial N_e}{\partial \lambda_{ap}}$</td>
<td>0.5946</td>
<td>0.6489</td>
</tr>
<tr>
<td>$\frac{2\partial N_l}{\partial \lambda_{ap}}$</td>
<td>0.2455</td>
<td>0.3027</td>
</tr>
</tbody>
</table>

The thermo-optic coefficients, calculated using these values in Eqs. (5) and (6), are shown in Table III. They lie above the thermo-optic coefficients of InP (1.95 × 10$^{-4}$ K$^{-1}$) and GaAs (2.35 × 10$^{-4}$ K$^{-1}$) (Ref. 5) and, as

would be expected because of the dispersion effects, the lower band gap material has a larger thermo-optic coefficient. Although there is little to compare with in the literature, the ratio between the two coefficients is, however, in excellent agreement with the results of a previous device study which reported a ratio of 0.81 between the thermo-optic coefficients of 1.1Q and 1.3Q.

In conclusion, we have demonstrated a method for determining the thermo-optic coefficients of MOVPE-deposited InGaAsP layers to a high accuracy. Very simple device structures, requiring only epitaxial multilayer deposition and no lithography, are described. The present studies are limited to reporting values at a wavelength of 1.55 µm and at a temperature of 25 °C, but this technique could be readily extended to cover the wavelength and temperature space required by device engineers.

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12. See www.photond.com for FIMMWAVE optical waveguide modeling software.