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Birefringence evaluation of multimode multilayer AlGaAs/AlAs waveguides

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We investigate surface-emitting second harmonic generation as a powerful technique for the evaluation of birefringence in optical waveguides supporting several modes. This one-shot diagnostic is demonstrated at 1319 nm in multilayer AlGaAs waveguides, before and after the lateral oxidation of AlAs layers. © 2001 American Institute of Physics.

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Nowadays material and device characterization for integrated optics has to face more and more stringent requirements, due to the tighter and tighter design compliances of state-of-the-art resonant/phase-matched devices. In spite of this, however, characterization tools are still essentially based on the measurement of waveguide effective indices and losses.¹ Concerning waveguide design, significant efforts have been recently undertaken to tailor modal birefringence (MB) with two main goals: (i) MB minimization for fiber-compatible, polarization-degenerate devices through geometrical compensation of material anisotropy;² (ii) controlled MB through form birefringence, for phase matching in parametric wavelength generators.³

In this letter we describe a one-shot technique which allows the simultaneous measurement of the TE/TM birefringence of all the eigenmodes supported by a multimode optical waveguide in a quadratically nonlinear composite semiconductor. Our approach exploits surface emitting second harmonic generation (SESHG), first demonstrated in 1981 using Ti:LiNbO₃ waveguides.⁴ SESHG has been later employed in GaAs/AlGaAs,⁵ and more recently in selectively oxidized GaAs/AlAs multilayers.⁶ The main concept underlying SESHG is sketched in Fig. 1 for a slab waveguide: the wave vector mismatch $\Delta\beta = \beta^+ - \beta^-$ between two nonlinearly interacting, counter-propagating eigenmodes at the fundamental frequency ω sets the out-of-plane emission angle θ for the radiated second harmonic 2ω . This angle relates to the sought information on MB, i.e., the difference $\Delta N = 2 \sin \theta$ between the effective indices of the counter-propagating fields at ω . The relation between these fields and the nonlinear polarization $\mathbf{P}^{(2\omega)}$ can be conveniently cast in the scalar form $P^{(2\omega)} = 2\varepsilon_0 d_{\text{eff}} E^+ E^-$, where ε_0 is the dielectric permittivity of vacuum and the effective coefficient d_{eff} depends on both the tensor structure and the polarizations of the coupled fields at ω , E^+ and E^- , respectively. Hereby, we refer to a GaAs-based guiding structure on (100) substrates, with $d_{\text{eff}} = d_{123}$, where SESHG is driven by the nonlinear

interaction of a TE with a TM mode oppositely propagating along the waveguide, with $\Delta\beta = \beta_{\text{TE}} - \beta_{\text{TM}}$. The simplest approach to excite SESHG consists in launching both TE and TM eigenfields at one input facet of the sample, exploiting the $\sim 30\%$ Fresnel reflection at the opposite semiconductor/air interface in order to generate the required counter-propagating cross-polarized modal components at ω . In this case, pictured in Fig. 2, two distinct out-of-plane emissions take place due to the interactions $E_{\text{TE}}^+ E_{\text{TM}}^-$ and $E_{\text{TM}}^+ E_{\text{TE}}^-$, respectively. These are associated with a stationary nonlinear polarization wave

$$\begin{aligned} P^{(2\omega)} &\propto E_{\text{TE}} E_{\text{TM}} \\ &= (A_{\text{TE}}^+ e^{-i\beta_{\text{TE}}z} + A_{\text{TE}}^- e^{i\beta_{\text{TE}}z})(A_{\text{TM}}^+ e^{-i\beta_{\text{TM}}z} + A_{\text{TM}}^- e^{i\beta_{\text{TM}}z}) \\ &= A_{\text{TE}}^- A_{\text{TM}}^+ e^{i\Delta\beta z} + A_{\text{TE}}^+ A_{\text{TM}}^- e^{-i\Delta\beta z} \\ &\quad + A_{\text{TE}}^+ A_{\text{TM}}^+ e^{-i(\beta_{\text{TE}} + \beta_{\text{TM}})z} + A_{\text{TE}}^- A_{\text{TM}}^- e^{i(\beta_{\text{TE}} + \beta_{\text{TM}})z} \\ &\approx 2r A_{\text{TE}}^+ A_{\text{TM}}^+ \cos(\Delta\beta z) \end{aligned} \quad (1)$$

with $r = A_{\text{TE}}^-/A_{\text{TE}}^+ \approx A_{\text{TM}}^-/A_{\text{TM}}^+$. The relevant term of $P^{(2\omega)}$ is the source of a surface-emitted field at 2ω , with $P^{(2\omega)} \propto \cos(\omega\Delta N z/c)$. It is therefore possible to evaluate the birefringence ΔN at ω by fringe counting in the near-field distribution of the harmonic $I^{(2\omega)}(z) \propto |P^{(2\omega)}|^2$, varying sinusoidally with period $\lambda/2\Delta N$.^{5,6} In a multimode waveguide, however, several TE–TM interactions can give rise to SESHG. While each (sign-reversed) pair produces a distinct (near-field) sinusoidal fringe pattern at 2ω , the visibility of

FIG. 1. Phase-matching scheme of SESHG at frequency 2ω from two nonlinearly interacting guided-wave fields at ω .

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FIG. 2. Sketch of SESHG with two out-of-plane emissions at opposite angles.

each depends strongly on: end-fire mode excitations, overlap integral between the counter-propagating fields associated with each SESHG process, coherence length and Maker-like interference in the second harmonic field at each depth within the thickness of the nonlinear film.⁷ For different launch conditions at ω , therefore, the near field at 2ω appears as either a single fringe system (fundamental mode coupling, TE_{00} – TM_{00} interactions), or a superposition of sinusoidal patterns (several mode couplings). In the latter case, the Fourier-transformed intensity distribution $I^{(2\omega)}$ in the far field can spatially resolve the phase-matched components originated by the corresponding SESHG processes, such that one observation can provide complete information on both birefringence and modal content of multimode waveguides.

To ascertain the applicability of the above approach, we performed experiments on AlGaAs waveguides. Samples were realized by molecular beam epitaxy according to the following structure: $Al_{0.7}Ga_{0.3}As$ (substrate)/AlAs (200 nm)/ $2 \times [Al_{0.1}Ga_{0.9}As$ (270 nm)/AlAs (25 nm)]/ $Al_{0.1}Ga_{0.9}As$ (270 nm)/AlAs (62 nm)/ $Al_{0.7}Ga_{0.3}As$ (300 nm)/GaAs (20 nm). The planar structures were reactively ion etched to create 1- μm -thick ridges with 3–9 μm widths and cleaved for end-fire excitation. For the measurements, we launched 100 ps pulses at $\lambda = 1.32 \mu m$ from a continuous wave (cw) mode-locked Nd-yttrium–aluminum–garnet laser (repetition rate 82 MHz) into the waveguides, using linearly polarized light at 45° relative to the substrate. With samples a few mm long, such pulse durations allow a quasi-cw interaction between the oppositely propagating waves. The ridges supported the four lowest-order quasi-TE and TM modes, and the light due to SESHG at $\lambda = 0.66 \mu m$ was collected by a charge coupled device (CCD) camera (a 4.8 mm $\times$ 3.6 mm Si array, with image resolution limited by a 320 $\times$ 240 pixel acquisition board).

The near-field measurement is illustrated in Fig. 3(a), where we also sketched the nonlinear polarization pattern. In the near field and for a sample length $L = 3.23 \pm 0.02$ mm, counting $m = 68.5 \pm 0.5$ fringes [see Fig. 4(a)], from $\Delta N = m\lambda/2L$ we could obtain the birefringence between the two fundamental modes: $N(TE_{00}) - N(TM_{00}) = 0.0140 \pm 0.0002$. For the relative uncertainty

$$\left| \frac{d(\Delta N)}{\Delta N} \right| = \left| \frac{dm}{m} \right| + \left| \frac{dL}{L} \right| + \left| \frac{d\lambda}{\lambda} \right|, \quad (2)$$

a typical value of 1.5% was achieved, the first term being the dominating one. In the conservative hypothesis that only an integer number of fringes could be counted in the image, any efforts to reduce the second term below $|dm/m| = 0.5/m$ proved not worthwhile, whereas the third term is typically

FIG. 3. MB evaluation through the detection of SESHG in: (a) near field, (b) far field.

much smaller than the first two. The overall figure [Eq. (2)] could be improved not only by increasing the pixel density, but also by using longer samples, provided that losses are negligible (as in our case, with typical values lower than 1 dB/cm).

In order to acquire the image of the far-field pattern, as sketched in Fig. 3(b), the SESHG was imaged onto the CCD with a lens of focal length $f = 2.5$ cm.⁶ Because of the CCD finite aperture w , the choice of f follows from the maximum amount of birefringence to be measured ($f \leq w/\Delta N_{\max}$). A typical result is shown in Fig. 4(b), where each pair of δ functions (Fourier transform of a sinusoid) refers to the corresponding set of counter-propagating modes. While the vertical extent of the δ 's is due to diffraction from the finite width of the ridge, lateral confinement bears no discernible effects on the observed pattern with respect to the case of a planar waveguide. From Fig. 4(b) it is straightforward to infer the value of MB for each couple of eigenmodes, as the ratio of the distance D_{ij} between the corresponding δ 's and the focal length, as presented in Table I. The case $N(TE_{10}) - N(TM_{10})$, although not visible in the photograph, was readily obtained by slightly changing the launch conditions,

FIG. 4. (a) Typical near-field intensity distribution $I^{(2\omega)}$. (b) Far-field picture of SESHG modes from an AlGaAs ridge 7 μm wide, for TE_{00} – TM_{00} (○), TE_{10} – TM_{00} (*), TE_{00} – TM_{10} (+). (c) Same as (b), after selective oxidation of AlAs layers.

TABLE I. Measured and calculated TE–TM modal birefringences.

Interacting modes	Measured ΔN	Calculated ΔN
TE ₀₀ –TM ₀₀	0.0138 ± 0.0008	0.014 ± 0.001
TE ₁₀ –TM ₀₀	0.125 ± 0.002	0.122 ± 0.002
TE ₀₀ –TM ₁₀	0.160 ± 0.002	0.158 ± 0.002
TE ₁₀ –TM ₁₀	0.0220 ± 0.0008	0.022 ± 0.001

and is also listed in the table. The uncertainties here are associated with both f and D

$$\left| \frac{d(\Delta N_{ij})}{\Delta N_{ij}} \right| = \left| \frac{d(D_{ij})}{D_{ij}} \right| + \left| \frac{df}{f} \right|. \quad (3)$$

While $|df/f| = 1\%$ after the manufacturer's specifications, the first term on the right-hand side of Eq. (3) depends on pixel discretization, i.e., on the resolution of both CCD and acquisition board. In fact, distances are measured in pixels (in our case the pixel size was $d_p = 15 \mu\text{m}$), and the relative uncertainty $|dD/D| \approx d_p/D$, which is lower for wider separated δ 's. The overall error ranges from 1.5% to 3%, with a smaller contribution given by the finite linewidths in the far field ($\sim 5 \mu\text{m}$ due to the finite waveguide length), and a negligible one by absorption.

In Table I the calculated ΔN 's and related uncertainties are also listed, as derived from Afromowitz's dispersion model⁸ (due to the ridge aspect ratio, a slab-waveguide mode solver was more than adequate). As apparent from Table I, this simple single-shot technique allows the accurate estimate of birefringence between all the existing modes at ω , in excellent agreement with model predictions.

Finally, we employed SESHG to investigate waveguides with a higher birefringence, i.e., AlGaAs/AlAs samples (as described above) after lateral oxidation of the AlAs layers.⁹ In general, due to form birefringence, the field in low-index layers is higher for TM than for TE polarization.^{3,6,10} It is therefore expected that by selectively lowering the refractive indices of thin AlAs layers, the effective indices of TM

modes decrease more than TE. This is experimentally verified and visible in Fig. 4(c), where two features are noticeable: on the one hand the MB between TE₀₀ and TM₀₀ is greatly enhanced by oxidation, from 0.0138 to 0.08.³ On the other hand, while $N(\text{TE}_{10}) \ll N(\text{TM}_{00})$ in the as-grown samples, oxidation lowers $N(\text{TM}_{00})$ far more than $N(\text{TE}_{10})$, thus reducing the corresponding MB from 0.125 to 0.11. Line pairs associated with larger ΔN 's fell outside the CCD field of view. Due to incomplete oxidation of AlAs layers through our process, such MB values were inferred from the experiment by assuming $n(\text{AlO}_x) = 1.61$,¹¹ and using the oxide penetration distance as a fitting parameter.

In conclusion, we have demonstrated that SESHG can be effective in characterizing modal birefringence of nonlinear waveguides with high accuracy. This technique is a valuable complement to standard m -line evaluation,¹⁰ and allows a precise spectral determination of phase mismatch in structures for parametric generation.

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