Second-harmonic generation through optimized modal phase matching in semiconductor waveguides

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We report optical second-harmonic generation (SHG) through modal phase matching in GaAs/AlGaAs semiconductor waveguides. Using femtosecond pulses, both type-I and type-II SHG is demonstrated for fundamental wavelengths near 1.55 μm. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1596726]

The nonlinear susceptibility of semiconductors is substantially higher than that in many ferroelectric crystals.[1] In GaAs, for example, the nonlinear susceptibility [$\chi^{(2)}$ $\sim$90 pm/V] is about three times higher than that in $LiNbO_3$. However, the isotropic nature of GaAs inhibits birefringent phase matching. Among the variety of quasiphase matching (QPM) schemes proposed for GaAs-based waveguides a patterned ion implantation technique was utilized to modulate the contribution of asymmetric quantum wells to the overall nonlinear susceptibility.[2] Modulation of bulk nonlinear susceptibility of GaAs through periodic crystal domain inversion has been achieved by organometallic chemical vapor deposition on a periodically inverted template fabricated by wafer bonding[3,4] or by domain disordering in AlAs/GaAs superlattices.[5] The fabrication of low-loss and thick layers of periodically inversed GaAs has been reported, with promising implication for the development of midinfrared optical parametric sources.[6] Based on the theory by van der Ziel[7] on phase-matched harmonic generation in a laminar structure, the experimental realization of birefringent phase matching (BPM) in GaAs/AlAs waveguides[8] was achieved using selective oxidation technique.

Modal phase matching (MPM) is a simple solution to the problem of phase velocity synchronism in nonlinear frequency conversion processes and is well known,[9,10] but has been of limited interest because of the poor spatial overlap between the interacting modes. However, using a proper waveguide design, the overlap integral between the third order mode and the fundamental can be optimized, resulting in a still appreciable effective nonlinearity. The expected normalized conversion efficiency, $P_{SH}/(P_{FF}^2 L^2)$, in optimized structures is lower, by a factor of 20, than in birefringent semiconductor waveguides and comparable with periodically poled $LiNbO_3$. On the other hand, there is no need for selective oxidation, as is the case in artificial birefringent waveguides, and hence, the structure can be combined with a laser diode on the same chip to provide a wholly integrated semiconductor light source based on nonlinear frequency conversion. Such a device is interesting for a range of applications, for example as a source of entangled photons in quantum optics and quantum cryptography.[11] In this letter we report second-harmonic generation (SHG) in such waveguides in the femtosecond regime. The use of femtosecond pulses allows high peak intensities without optical damage to the waveguides and has potential for telecommunication applications.

The sample was grown on a semi-insulating GaAs substrate by a Varian molecular beam epitaxy machine. The epitaxial structure used was 1000 nm $Al_{0.98}Ga_{0.02}As$/130 nm $Al_{0.25}Ga_{0.75}As$/260 nm $Al_{0.50}Ga_{0.50}As$/130 nm $Al_{0.25}Ga_{0.75}As$/1000 nm $Al_{0.98}Ga_{0.02}As$/30 nm GaAs. Optical ridges were etched chemically in order to provide two-dimensional confinement. Ridge width varied from 3 to 5 μm and the waveguide length was initially 3.0 mm. The optimized structure is a type of "M" waveguide, designed for maximum overlap between the TE_2 (third order) mode at the second-harmonic (SH) frequency and TE_0 and TM_0 modes at the fundamental frequency [Fig. 1(a)]. This is a type-II phase matching scheme, allowed by the selection rules of GaAs second-order susceptibility tensor in the case of a ⟨1,0,0⟩ growth and a waveguide oriented along the ⟨0,1,1⟩ axis.[9] Type-I phase matching is also possible (TM_2 at SH and TE_0 at fundamental) at slightly shorter wavelengths. Overlap is enhanced by the characteristic M profile of the waveguide core as shown in Fig. 1(b). A comprehensive theoretical study of this structure is reported elsewhere.[12,13] The losses at 1.55 μm, measured using the scattering technique,[14] were $\sim$2.7 cm^{-1} for TE input polarization and $\sim$3.5 cm^{-1} for TE+TM input polarization. Near 0.82 μm the losses were $\sim$1.1 cm^{-1} for TE polarization and $\sim$1.0 cm^{-1} for TM polarization. It is very difficult to estimate the losses at second harmonic (second order mode) using either the scattering or Fabry–Pérot techniques. Details of the complete experimental setup were reported earlier.[15] Near-transform limited fundamental pulses of $\sim$250 fs duration and $\sim$10 nm spectral full width at half maximum (FWHM) with average power levels of $\sim$70 mW

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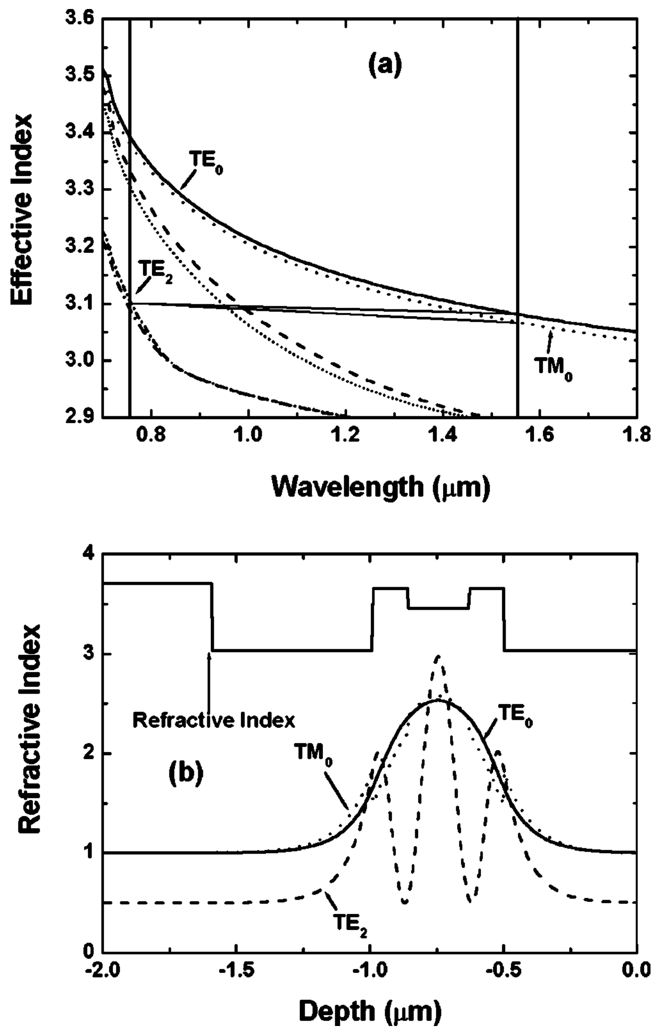

FIG. 1. (a) Dispersion of the effective indices of the first three modes in both polarizations (TE upper, TM lower curves), illustrating the principle of modal phase matching: chromatic dispersion is compensated with the waveguide dispersion. The waveguide geometry is defined such that the third order mode at 0.775 μm has the same phase velocity as the fundamental mode at 1.55 μm. (b) Waveguide refractive index and intensity distribution $|E^2|$ of modes TE_0, TM_0 at 1.55 μm and TE_2 at 0.775 μm.

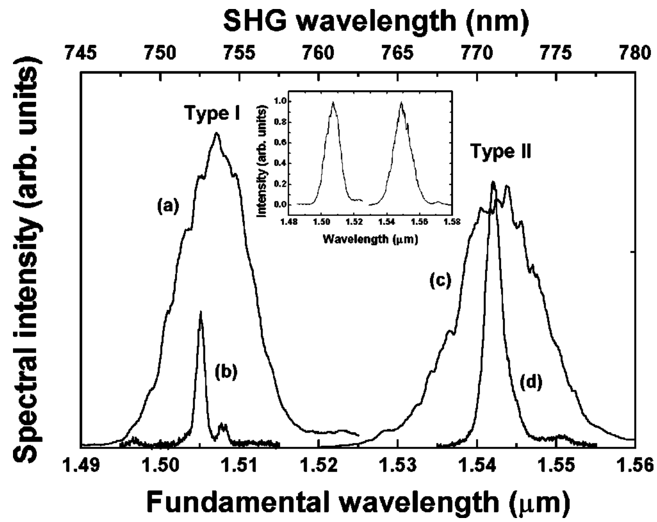

FIG. 2. Typical transmitted fundamental spectra [curves (a) and (c)] for type-I and type-II interactions, respectively, and the corresponding SHG spectra [curves (b) and (d)]. Input spectra are provided in the inset. The vertical axis indicates the relative strength of each process.

were used in the experiment. A long-pass filter blocked any residual light below 0.85 μm, while a half wave plate controlled the fundamental polarization. The sample was mounted on an end-fire coupling rig. Light was coupled into the waveguide via a X40 microscope objective and a X20 objective was used to collect the generated SH and the transmitted fundamental. A semiconductor head power meter, sensitive in the 0.4–1.0 μm spectral range, was used to measure the SHG output power.

A clear growth of SHG signal was observed for appropriate tuning of the fundamental wavelength and for both TE and TE+TM input polarizations. A polarizing beam splitter inserted before the power meter allowed the investigation of polarization state of the generated signal. It was established that the generated output was TM (TE) polarized for TE (TE+TM) input, indicating phase-matched type-I and type-II interactions, respectively. An IR spectrum analyzer was used to record the spectra of the generated SH and the transmitted fundamental. A typical set of spectra, supporting phase matched SHG, is shown in Fig. 2. It is evident that type-I process takes place at $\sim$1.505 μm and type-II at $\sim$1.540 μm. The corresponding SHG spectra present a FWHM spectral width of $\sim$0.5 and $\sim$1 nm, respectively. In our case the fundamental had a spectral FWHM of $\sim$10 nm, therefore only a fraction of the input bandwidth is used in the conversion process. This effect can be viewed in the temporal domain as only a part of the pump wave packet having phase velocity that can be matched at the second harmonic. When the conversion efficiency is high enough, the pump experiences a partial depletion reminiscent of spectral hole burning. This has indeed been observed in birefringent waveguides.[15] Under the same experimental conditions, no depletion of the fundamental was observed using modal phase matched samples, thus indicating lower conversion efficiency.

Further evidence of phase matching was obtained by measuring the generated SH power as a function of input power. The expected quadratic dependence was confirmed, with best fits to the slope yielding values of $\sim$2.0, on a log–log plot. A representative set of such measurements, for the same waveguide and for both type-I and type-II interactions, is shown in Fig. 3. A small reduction in the slope could be observed for a number of waveguides for average input powers above 30 mW. We also observed nonphase-matched SHG, which was $\sim$25 times lower in magnitude than the phase-matched signal, with a FWHM bandwidth of $\sim$5 nm providing a strong evidence that we were characterizing a phase-matched process. Figure 4 shows the SHG power plotted as a function of central wavelength of the fundamental spectrum for a fixed input power of $\sim$20 mW. From the plots acceptance bandwidths (FWHM) of $\sim$11 nm ($\sim$10 nm) were obtained corresponding to type-I (type-II) phase matching.

Maximum SHG power was measured after cleaving the sample to 1.5 mm. For type-I interaction we measured $\sim$2.6 μW of SHG power after the output objective for $\sim$80 mW of input fundamental power before the input objective. For type-II interaction we detected a maximum SHG power of $\sim$10.3 μW for $\sim$65 mW of input power. These values represent an increase of $>$50% compared to the ini-

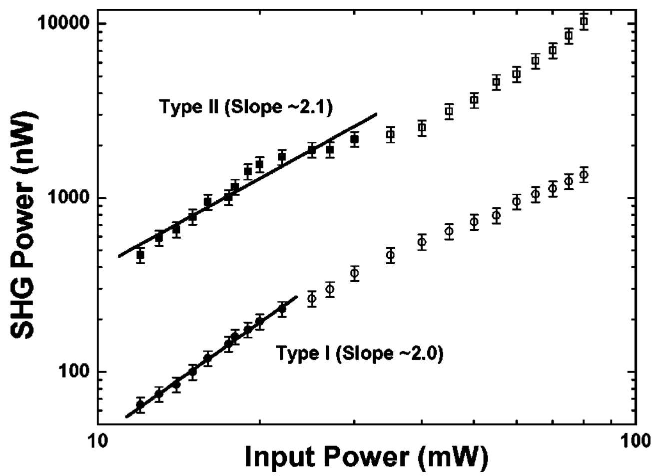

FIG. 3. The second-harmonic average output power as a function of the fundamental average input power. Scattered points are the experimental data and the solid lines are the best fits.

tial 3 mm long waveguides, indicating high SHG transmission loss. It should be noted that while using ~250 fs pulses the interaction length, limited by group velocity mismatch, is shorter than the physical length. Therefore, a longer device tends to have a lower yield because of propagation loss at the second harmonic. The maximum external efficiency (SHG power after the output objective/launched power before the input objective) of the present device was ~0.015% for type-II geometry. A quick, qualitative comparison with recent demonstrations of femtosecond SHG in III–VI waveguides using the same experimental set up reveals that the external efficiency of the MPM sample is at least two times higher than that obtained by the QPM device reported in Ref. 16. However, it is almost two orders of magnitude lower than the efficiency of the BPM sample (650 μW of SHG).[15] To explain such low efficiency values we need to consider a number of factors. We estimated that <20 mW of fundamental power is coupled into the waveguide accounting for the losses due to input objective, the input facet reflectivity and the mode-matching factor. This is well supported by transmission measurements, which indicated that ~7% of the available input power is in fact collected after the output objective. This factor is slightly lower in the case of BPM sample reported in Ref. 15. The collection efficiency of the generated SHG was <30% (lower than in Ref. 15) because of high divergence and high output facet reflectivity of the third order mode (the modal reflectivity could be as high as ~50% according to the model of Ref. 17). Based on the earlier factors an internal efficiency (Coupled fundamental power/SHG power inside the waveguide) of >0.15% was estimated for the type-II process. An estimated group velocity walk-off length of ~100 μm indicates that the actual conversion efficiency could be even higher. The main difference between birefringent waveguides operating on fundamental modes and modal waveguides is the overlap integral ($0.6\ \mu m^{-0.5}$ in case of BPM and $0.14\ \mu m^{-0.5}$ in case of MPM), which yields a difference in efficiency by a factor of ~20. The additional factor of 5 could be explained by the poor confinement of the SH wave.

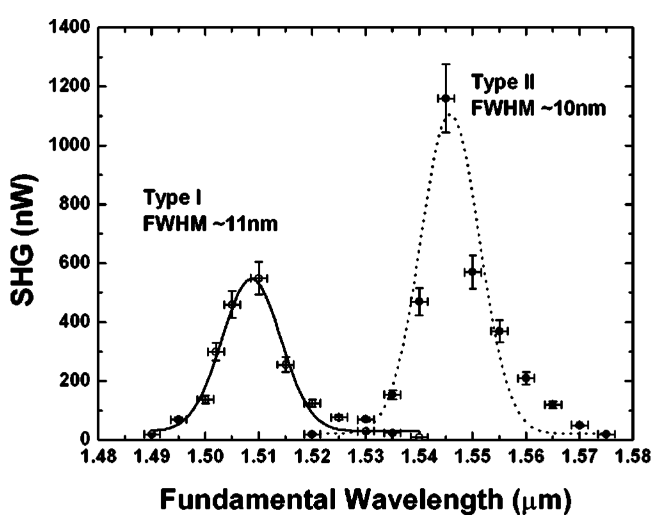

FIG. 4. Phase matching acceptance bandwidth curves showing the SHG power as function of the fundamental center wavelength. Scattered points are the experimental data and the solid lines are the best fits.

In conclusion, we have demonstrated nonlinear frequency conversion in III–V semiconductor waveguides using modal phase matching. Both type-I and type-II SHG were observed for fundamental wavelengths near 1.55 μm, using femtosecond pulses. Practical SHG average powers of up to 10 μW were obtained with an average input power of 65 mW for the most efficient type-II interaction. This translates to a maximum overall device efficiency of 0.015% corresponding to an internal efficiency of >0.15%.

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