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Second-harmonic generation at $\lambda = 1.6$ μm in AlGaAs/Al_2O_3 waveguides using birefringence phase matching

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We demonstrate phase-matched second-harmonic generation from a $\lambda = 1.6$ μm pump in a GaAs-based waveguide. Phase matching is obtained by using the form birefringence in an AlGaAs/Al_2O_3 multilayer obtained by selective wet oxidation. © *1998 American Institute of Physics.* [S0003-6951(98)04523-9]

Gallium arsenide is an outstanding nonlinear optical material, thanks to its high second-order nonlinear coefficient, wide transparency in the infrared, and possibility of integration with sources. However, phase matching for nonlinear frequency conversion is difficult to achieve in this isotropic, highly dispersive semiconductor. Although quasimatching by domain reversal was recently demonstrated in GaAs waveguides,[1] very high scattering losses result from the domain reversal process. Recently, we have proposed[2] a new approach to phase-match nonlinear frequency conversion in GaAs/AlAs waveguides. As was originally pointed out by van der Ziel,[3] form birefringence in multilayers can be used to obtain phase matching. However, from birefringence in GaAs/AlAs multilayers is too low, due to the low refractive index contrast [n(GaAs)-n(AlAs)$\approx$0.6]. Using selective wet oxidation of AlAs,[4] (Al)GaAs/Al_2O_3 multilayer waveguides can be fabricated,[5] which present a large birefringence thanks to the high index contrast between GaAs and Al_2O_3 [n(GaAs)-n(Al_2O_3)$\approx$2]. This birefringence is sufficient to phase-match nonlinear frequency conversion in the near and mid-infrared. This technique has been used to demonstrate phase-matched difference frequency generation of 4 (Ref. 6) and 5.3 (Ref. 2) μm radiation in GaAs-based waveguides. Birefringence phase matching can also be applied to second-harmonic generation (SHG) and frequency conversion around 1.55 μm, a frequency region of interest for telecommunications. In this case, however, the second-harmonic (SH) frequency is necessarily close to the band edge of AlGaAs and a much higher birefringence is needed in order to compensate for the high dispersion. In this letter, we demonstrate birefringence phase-matched frequency doubling of a 1.6 μm pump in a AlGaAs/Al_2O_3 waveguide. Since the phase-matching condition is the same for SHG and frequency mixing, this also demonstrates that this technique is viable for wavelength conversion applications around 1.55 μm.

The phase-matching condition for SHG reads:

$$n_{\mathrm{TE}}(\omega) = n_{\mathrm{TM}}(2\omega). \tag{1}$$

To insure transparency at the SH frequency, we choose the waveguide core to be a $Al_{0.3}Ga_{0.7}As$/AlAs multilayer, where the AlAs is selectively transformed in Al_2O_3 by the post-growth wet oxidation process. In the oxidized multilayer, both the transverse-electric (TE) and the transverse-magnetic (TM) mode effective indices are lowered by the presence of the low index oxide, the TM index being more affected due to its higher overlap with the oxide.[2] Phase matching is obtained with $n_{\mathrm{TE}}(\omega) = n_{\mathrm{TM}}(2\omega) \approx 3.1$. To confine the waves, we thus need a cladding layer with refractive index n(cladding)<3.1. This is difficult to find at the SH frequency, since only high Al composition $Al_xGa_{1-x}As$ ($x>0.8$) has $n<3.1$ at $\lambda \approx 0.8$ μm. Unoxidized AlGaAs cannot be used as a cladding layer, since a high Al-composition layer would in fact readily oxidize along with AlAs. On the other side, use of a single Al_2O_3 cladding layer would require an oxidized thickness greater than 300 nm, which results in excessive strain and mechanical instability of the layer. To overcome this problem, we have used an antiresonant design for the cladding layer (Fig. 1). The SH wave is confined by a series of low-index Al_2O_3 multiple reflectors, separated by resonant $Al_{0.7}Ga_{0.3}As$ layers. The wave experiences a frustrated total reflection at each $Al_{0.7}Ga_{0.3}As/Al_2O_3$ interface. The $Al_{0.7}Ga_{0.3}As$ thicknesses are chosen so that the reflected waves are in phase. This results in less than 0.1 dB/cm calculated diffraction loss for the SH TM wave with only three Al_2O_3 layers of 120 nm total thickness. This design combines the concepts of Bragg waveguide[7] and ''ARROW B.''[8] At the pump frequency, on the contrary, the $Al_{0.7}Ga_{0.3}As$ refractive index is lower than the effective index of the TE mode, so that the pump wave is evanescent in these layers. To summarize, the $Al_{0.7}Ga_{0.3}As/Al_2O_3$ multilayer cladding acts as a resonant re-

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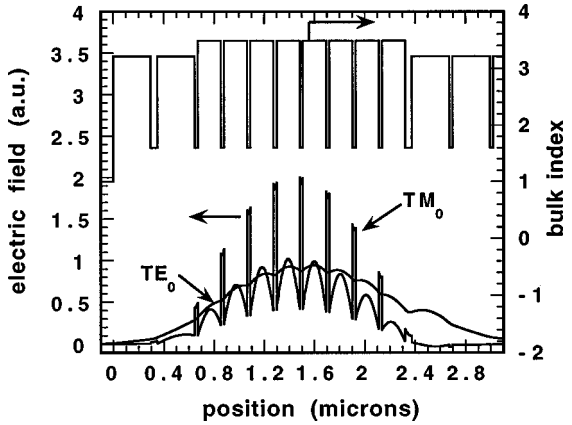

FIG. 1. Calculated electric fields of $TE_0(\omega)$ and $TM_0(2\omega)$ in the oxidized waveguide (left axis). The index profile at 2ω in the waveguide is also shown (right axis). They central multilayer is composed of $Al_{0.3}Ga_{0.7}As/Al_2O_3$, the cladding of $Al_{0.7}Ga_{0.3}As/Al_2O_3$.

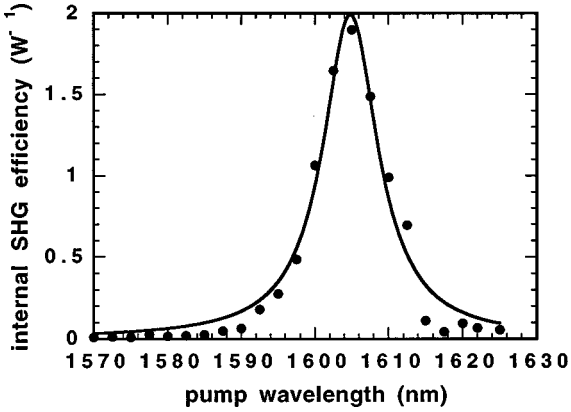

FIG. 3. Measured second-harmonic generation efficiency ($\eta \equiv P_{2\omega}/P_{\omega}^2$) in a 1.7 mm long waveguide as a function of pump wavelength. The continuous line is a Lorentzian fit.

flector for the SH wave and as a conventional cladding for the pump wave. Figure 1 shows the calculated TE and TM fields at 1.57 and 0.785 μm, respectively. The waveguide structure before oxidation consists of: (GaAs substrate)/2 μm $Al_{0.7}Ga_{0.3}As$/30 nm AlAs/296 nm $Al_{0.7}Ga_{0.3}As$/30 nm AlAs/296 nm $Al_{0.7}Ga_{0.3}As$/62.5 nm AlAs/ $8x$ (184 nm $Al_{0.3}Ga_{0.7}As$/30 nm AlAs)/296 $Al_{0.7}Ga_{0.3}As$/62.5 nm AlAs/296 nm $Al_{0.7}Ga_{0.3}As$/30 nm $Al_{0.3}Ga_{0.7}As$ cap layer. All AlAs layers transform into Al_2O_3 after oxidation. In the simulation we assumed $n(Al_2O_3)=1.6$ and a 15% contraction of the oxidized layers. Both the pump and SH waves are well confined in the $Al_{0.3}Ga_{0.7}As/Al_2O_3$ core multilayer. The calculated birefringence at $\lambda=1.06$ μm is: $n(\mathrm{TE})-n(\mathrm{TM})=0.28$. Figure 2 shows the effective indices of the pump and SH modes as a function of frequency. Phase matching is expected at $\lambda_{\mathrm{pump}}=1574$ nm.

The sample was grown by molecular beam epitaxy on a semi-insulating (001) GaAs substrate. A double-step, reactive ion etching processing[5] was used to define 3 μm wide, 1.3 μm deep ridge waveguides on the top of 100 μm wide, 2 μm deep ridges. The 3 μm ridges provide the lateral optical confinement, whereas the 100 μm ridges expose the AlAs layers for lateral oxidation. The sample was oxidized for 2 h at 400 °C in a water vapor atmosphere obtained by bubbling

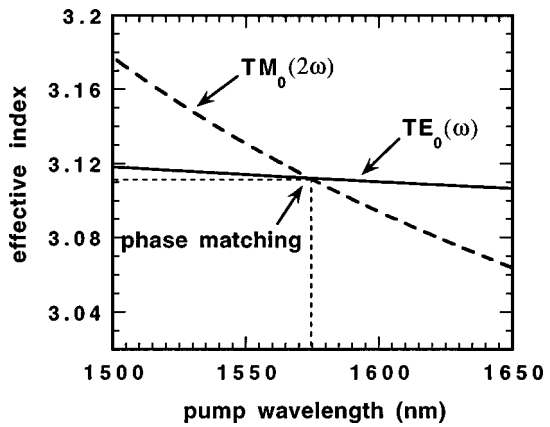

FIG. 2. Calculated effective indices $TE_0(\lambda)$ and $TM_0(\lambda/2)$ in the oxidized waveguide as a function of pump wavelength λ. Phase matching occurs at $\lambda=1574$ nm.

a N_2 carrier gas through water at 95 °C. Oxidation was observed to proceed laterally from the edge of the 100 μm ridges and oxidize the AlAs underneath the 3 μm ridges. The loss for the TE mode at $\lambda=1.32$ μm was measured to be: 8 dB/cm. We stress that due to the high birefringence the TM mode is under cutoff at this wavelength.

A mode-locked, tunable color center laser was used as a pump in the SHG experiment. The 76 MHz, 8 ps pulses were end-fire coupled into a 1.7 mm long waveguide. The SH output beam was filtered and detected by a cooled CCD camera. The SH power measurement was calibrated using a Ge detector. Figure 3 shows the SH conversion efficiency (average guided SH power divided by the square of the average guided pump power) as a function of pump wavelength, together with a Lorentzian fit. Both SH and pump powers in the wavelength were estimated from the measured 11% coupling efficiency. A clear phase-matching peak is observed at 1605 nm, corresponding to the TE_0, TM_0 interaction. The small discrepancy with the expected phase-matching resonance (1570 nm) can be attributed to imperfect knowledge of bulk indices and layer thickness. The maximum average SH power is 2.3 μW, with 1.1 mW average pump power coupled into the waveguide. Another weaker pump (not shown) was observed at $\lambda=1500$ nm, corresponding to phase matching between higher order modes, which have a smaller overlap. Taking into account the 6.1×10^{-4} duty factor, the conversion efficiency for cw beams at the TE_0-TM_0 resonance is: $\eta=0.12\%$ W^{-1}. This is much smaller than the calculated efficiency: $\eta=81\%$ W^{-1} for $L=1.7$ mm. The low experimental conversion efficiency is due to the loss at the SH wavelength. Transmission measurements as a function of wavelength were performed. Transmission in the oxidized waveguide strongly decreases below 1 μm, and the absorption length is estimated to be few tens of microns at 0.8 μm for both TE and TM polarizations. Unoxidized waveguides are on the contrary transparent down to 0.7 μm. The effect of loss is also evident in the width of the phase-matching resonance. Assuming a power loss coefficient α at the SH wavelength, and no loss at the pump wavelength, the SHG conversion efficiency, $\eta \equiv P_{2\omega}/P_{\omega}^2$, can be written as a function of frequency as

$$\eta(\omega) \propto \frac{1}{(\alpha/2)^2 + (k_{2\omega} - 2k_{\omega})^2}, \tag{2}$$

where $k_{2\omega} - 2k_{\omega}$ is the phase mismatch between the pump and the second harmonic. From the fit to the experimental phase-matching width, an absorption coefficient $\alpha = 470$ cm^{-1} is deduced.

We observed these losses in the near infrared in other oxidized samples. These losses are clearly related to oxidation (since they are not present in the waveguide before oxidation). They are not due to diffraction towards the substrate or scattering at the wavelength surface or sidewalls, since these mechanisms would produce an opposite wavelength dependence. Scattering by small microcristallites in the Al_2O_3 can also be excluded, since the observed wavelength dependence is much stronger than the typical $1/\lambda^4$ Rayleigh scattering dependence. Al_2O_3 itself is known to be transparent in the near infrared. We therefore attribute these losses to absorption by levels introduced in the gap of $Al_{0.3}Ga_{0.7}As$ by the oxidation of surrounding AlAs layers. It was already shown[9] that excess As produced by the oxidation reaction can remain in the crystal forming As antisites. These defects introduce donor levels at the midgap[9] and produce Fermi level pinning. Similar midgap defects related to excess As cause near-infrared losses in low-temperature grown GaAs.[10] The same mechanism may be at the origin of absorption in $AlGaAs/Al_2O_3$ waveguides. This absorption may then be reduced by using rapid thermal annealing[10] or changing the growth conditions.

In conclusion, we demonstrated frequency doubling of a 1.6 μm pump in multilayer $AlGaAs/Al_2O_3$ waveguides. To confine the SH wave, we used an antiresonant cladding made of Al_2O_3 multiple reflectors. The SHG conversion efficiency is 190% W^{-1} (pulsed) and 0.12% W^{-1} (cw). The conversion efficiency was limited by absorption loss at the SH wavelength. This demonstrates that the concept of form birefringence phase matching can be used to obtain frequency conversion in the near infrared in GaAs-based waveguides. This approach can be easily extended to cover the $\lambda \approx 1.55$ μm band of interest for telecommunications.

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