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Phase-matched mid-infrared difference frequency generation in GaAs-based waveguides

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We demonstrate difference frequency generation of 4 μm radiation from 1 to 1.32 μm pumps in GaAs-based waveguides. Phase matching is obtained by using form birefringence in selectively oxidized AlGaAs/AlAs multilayers. A tunability over 50 cm⁻¹ around 4 μm is demonstrated by changing the waveguide temperature and one pump wavelength. A much larger tunability may be achieved by using two tunable sources. © 1997 American Institute of Physics.

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Gallium arsenide and aluminium gallium arsenide have very high second-order susceptibilities [χ(2)(GaAs)] = 240 pm/V in the near infrared (NIR). This fact, together with the possibility of integration with laser sources, makes these materials very attractive for nonlinear frequency converters. Frequency conversion in GaAs-based waveguides may lead to widely tunable infrared sources by difference frequency generation (DFG), frequency converters around 1.55 μm, and all-optical processing at 1.55 μm. However, phase matching is difficult to achieve due to the absence of natural birefringence in these cubic semiconductors. Although quasi-phase matching was recently demonstrated in GaAs waveguides, the high scattering losses limit the useful interaction length to about 1 mm. We recently proposed to use the huge form birefringence in multilayer AlGaAs/(Al oxide) waveguides to achieve phase matching. These high-index contrast multilayers are obtained by selective lateral oxidation of AlGaAs/AlAs hetrostructures. A form birefringence as high as 0.2 was measured in oxidized multilayer GaAs/AlAs waveguides. Such birefringences are sufficient to phase match both DFG in the infrared and frequency conversion around 1.55 μm. In this letter we demonstrate phase-matched DFG of mid-infrared (MIR) 4 μm radiation from two near-infrared 1–1.32 μm pumps in an oxidized waveguide. The phase-matching condition for this interaction, \( n_{TM}(\omega_1)\omega_1 - n_{TE}(\omega_2)\omega_2 = n_{TE}(\omega_2)\omega_3 \), can be written as

\[
n_{TM}(\omega_1)\omega_1 - n_{TE}(\omega_2)\omega_2 = n_{TE}(\omega_2)\omega_3,
\]

where \( \omega \) are the frequencies of the interacting waves, \( \omega_1 = \omega_2 \), and \( n_{TE}, n_{TM} \) are the effective indices in the waveguide. The higher frequency pump at \( \omega_1 \) propagates in the lower index mode TE, in order to compensate for the strong dispersion of AlGaAs in the near-infrared.

The sample was grown on a n-doped (001) GaAs substrate and consists of: GaAs substrate/2000 nm AlAs/100 nm Al\(_{0.3}\)Ga\(_{0.7}\)As/1000 nm Al\(_{0.7}\)Ga\(_{0.3}\)As/50 nm AlAs/510 nm Al\(_{0.7}\)Ga\(_{0.3}\)As/50 nm AlAs/300 nm Al\(_{0.3}\)Ga\(_{0.7}\)As/30 nm AlAs/300 nm Al\(_{0.7}\)Ga\(_{0.3}\)As/30 nm AlAs/300 nm Al\(_{0.7}\)Ga\(_{0.3}\)As/75 nm AlAs/510 nm Al\(_{0.7}\)Ga\(_{0.3}\)As/30 nm Al\(_{0.3}\)Ga\(_{0.7}\)As. After oxidation, all AlAs layers, except the 2000 nm layer on the substrate side, are selectively converted into a low-index (n = 1.6) Al-oxide ("Alox"). The nonlinear susceptibility of this amorphous layer is equal to zero, and the nonlinear process completely occurs in the GaAs layers. Figure 1 shows the calculated electric fields \( TE_0(1.32 \mu m) \), \( TM_1(1.01 \mu m) \), \( TE_0(4.3 \mu m) \) in this waveguide. We assumed a 20% reduction of the oxidized layer thicknesses. The waveguide core is composed by the three-period (Al\(_{0.3}\)Ga\(_{0.7}\)As/Alox) multilayer. The pump waves are strongly confined in this high birefringence multilayer thanks to two Alox barriers, which act as low-index cladding layers. The barrier on the substrate side has been split into two thinner (50 nm) Alox layers, since stress-induced delamination seems to be more likely in thicker oxide layers. The bottom unoxidized AlAs layer was added as a cladding layer for the MIR wave. We stress that the pump TM mode effective index is lower than the Al\(_{0.7}\)Ga\(_{0.3}\)As index. This implies that the TM mode, which is localized in the oxidized multilayer, is not the fundamental mode of the overall structure. This TM₁ mode is confined in the central core only by virtue of the Alox barriers. According to simulation, these three modes satisfy the phase-matching condition (1). The calculated birefringence at \( \lambda = 1.06 \mu m \) is: \( \Delta n = n(TE_0) - n(TM_1) = 0.142 \).

By using a double-step processing, 3-μm-wide and 1.05-μm-deep ridge waveguides were defined on the top of 100-μm-wide, 1.7-μm-deep ridges. The sample was oxidized for 1 h 20 min at 400 °C in a water-vapor atmosphere obtained by passing a N\(_2\) carrier through a bubbler at 95 °C. The oxidation proceeded laterally from the edge of the 100 μm-deep ridge waveguides well below the 3 μm ridges. Figure 2 shows a

![Electric field in the oxidized multilayer waveguide](image)

**FIG. 1.** Electric fields in the oxidized multilayer waveguide: \( TE_0(\lambda = 1.32 \mu m) \) (thick continuous line), \( TM_1(\lambda = 1 \mu m) \) (thin continuous line), \( TE_0(\lambda = 4 \mu m) \) (dashed line). The gray zones indicate the Alox layers.
scanning electron micrograph of an oxidized 3 \( \mu \text{m} \) ridge waveguide. The birefringence was measured by coupling a mode-locked Nd:YAG laser in the waveguide and measuring the angle between the two second-harmonic surface-emitted waves.\(^7\) The measured birefringence, \( \Delta n(\lambda = 1.06 \ \mu \text{m}) = 0.139 \) is in good agreement with the calculated value.

A cw Nd:YAG laser (\( \lambda = 1.32 \ \mu \text{m} \)) and a tunable cw Ti:Sa laser were simultaneously end-fire coupled in a 3-\( \mu \text{m} \)-large, 1.2-mm-long oxidized waveguide in the TE and TM polarization, respectively. The infrared signal generated in the waveguide was collected by an achromatic BIORAD microscope objective \( f = 13.3 \ \text{mm}, \text{N.A.} = 0.5 \), filtered by a Ge plate and measured by an InSb detector. Figure 3 shows the measured MIR signal power as a function of the Ti:Sa wavelength. The pump powers, measured at the output of the waveguide, are: \( P(\text{YAG}) = 0.2 \ \text{mW}, \ P(\text{Ti:Sa}) = 2.2 \ \text{mW} \). The 1-nm-wide phase-matching peak at \( \lambda(\text{Ti:Sa}) = 0.9958 \ \mu \text{m} \) corresponds to a 4.04 \( \mu \text{m} \) infrared wavelength. This signal is TE polarized, as required by Eq. (1). Figure 4 shows the infrared power at the phase-matching peak as a function of the product of pump powers. The noise at high pump powers is due to thermal instabilities related to the Fabry–Perot effect. The linear fit gives a conversion efficiency: \( \eta = 0.043\% \ \text{W}^{-1} \), and a normalized efficiency: \( \eta_{\text{norm}} = 3\% \ \text{W}^{-1} \ \text{cm}^2 \). This value is a factor of 50 lower than the calculated one: \( \eta_{\text{norm}}(\text{theor}) = 160\% \ \text{W}^{-1} \ \text{cm}^2 \). This difference is attributed to high scattering losses for the MIR signal. As it is clear from Fig. 1, the MIR wave has a large electric field at the semiconductor/air interface. Since this interface presents some residual roughness, very strong scattering losses result. Low losses were first measured in the NIR by the Fabry–Perot fringes method\(^8\) at \( \lambda = 1.32 \ \mu \text{m} \): \( \alpha(\text{NOX}) = 5 \ \text{dB/cm}, \ \alpha(\text{OX}) = 7 \ \text{dB/cm} \), before and after oxidation respectively. Losses have also been characterized in the MIR by waveguided Fourier transform infrared spectroscopy. It was observed that without the 3-\( \mu \text{m} \)-wide ridge waveguide, losses were identical in the near and in the mid-IR. However, the difference frequency experiments performed with the 3 \( \mu \text{m} \) ridge and with different sample lengths lead to the measurements of higher mid-IR losses, up to 50 cm\(^{-1} \). We conclude from these cross experiments that the main origin of losses comes from the scattering on the ridge edges. This is consistent with the fact that NIR losses are found to be much lower (7 dB/cm), due to the low overlap of the NIR modes with the etched interfaces. The small increase of NIR losses observed between before (5 dB/cm) and after oxidation (7 dB/cm) is attributed to an increase of this overlap consecutive of the index modification in the multilayer, with maybe small residual absorption losses in oxidized AlAs, which were however not measurable. This will be published in details elsewhere.

The tunability of this infrared source was also studied. The phase-matching condition [Eq. (1)] and the energy con-
servation ($\omega_2 = \omega_1 - \omega_3$), impose two conditions on the three frequencies $\omega_1, \omega_2, \omega_3$. The signal frequency can thus be tuned by changing both pump frequencies. We calculate 0.25 $\mu$m tunability around 4 $\mu$m with 50 nm tunability on the pumps. Since in our setup only one laser is tunable, we change the guide temperature as a second parameter. Figure 5 shows the generated infrared wavelength as a function of temperature. We measure a linear variation with a slope: $\Delta \lambda / \Delta T = 1.2$ nm/°C. With $\Delta T = 70$ °C a $\Delta \lambda = 0.09$ $\mu$m (50 cm$^{-1}$) tunability is obtained around 4 $\mu$m. Our calculations show that the temperature tunability can be enhanced by a factor of 5 by using pump energies near to the band gap.

In conclusion, we have demonstrated tunable infrared ($\approx 4$ $\mu$m) generation by DFG from two near-infrared pumps (1–1.32 $\mu$m) in selectively oxidized AlGaAs/AlAs waveguides. The 3% W$^{-1}$ cm$^{-2}$ conversion efficiency is presently limited by losses in the infrared. The generated wavelength could be tuned over 50 cm$^{-1}$ by changing the guide temperature and one pump’s wavelength. Much larger tunabilities are expected by use of two tunable sources. By reducing losses, using longer waveguides and improving coupling, we expect to achieve mid-infrared powers in the tens of $\mu$W range from low-power near-infrared laser diodes. This might also open the way to fully-integrated diode-pumped optical parametric oscillators in the 4–6 $\mu$m region.

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