

Ultra-broadband, high-gain, polarization-independent optical parametric amplification in type-II quasi-phase-matched AlGaAs waveguides

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Abstract: We discuss a dispersion-managed non-birefringent type-II quasi-phase-matched (QPM) aluminum-gallium-arsenide (AlGaAs) waveguide, achieving 22.4 dB gain with ± 0.5 dB uniformity across 334 nm-band centered at 1550 nm with 17 mW pump power.

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1. Introduction

Optical parametric amplifiers (OPA) offer several important advantages compared to rare-earth-ion-doped amplifiers, namely low-noise, broadband operation and tunable operating wavelength. OPAs work as a frequency mixer, where a pump wave amplifies an incoming optical signal generating a mixing wave product (idler). Second-order optical nonlinearity ($\chi^{(2)}$) processes (e.g. difference frequency generation, DFG) has advantages to conventional ($\chi^{(3)}$) processes (e.g. four wave mixing), namely ultra-low crosstalk (< -40 dB), high efficiency and low pump power (< 50 mW), wide (> 300 nm) and uniform (< 0.5 dB ripple) parametric gain (> 20 dB) with polarization-independent operation. Ref [1] demonstrated polarization insensitive wavelength conversion using DFG over 40 nm 1-dB-bandwidth utilizing type II quasi-phase-matched AlGaAs waveguides. This paper presents order of magnitude wider conversion bandwidth (334 nm 1-dB-bandwidth), four orders of magnitude higher gain (22.4 dB for a 20 mm-long device at 17 mW pump power), and highly uniform gain (0.5 dB ripple across the 1-dB-bandwidth) by employing an innovative dispersion-managed waveguide design.

2. Theoretical background

We consider the $\chi^{(2)}$ process in highly nonlinear AlGaAs material ($\chi^{(2)} \sim 100$ pm/V for $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$). The Type-II interaction occurs between TE-polarized 775 nm continuous wave pump and TM(TE)-polarized input signal in the 1550 nm band, resulting in TE(TM)-polarized idler in the 1550 nm band. Efficiency of the process (eq.1.) depends on the phase matching condition [2].

$$\eta_{ni} = \eta_{norm} L^2 \propto \frac{\chi^{(2)^2}}{n^3} \frac{L^2}{A_{eff}} \text{sinc}^2\left(\frac{\Delta\beta L}{2}\right) \quad (1)$$

where A_{eff} is the effective area of the modal interaction, L is the interaction length, and $\chi^{(2)}$ is the second-order nonlinear optical susceptibility. The mismatch in the propagation constants of the interacting waves results in non-zero $\Delta\beta$, causing reduction in the conversion efficiency. $\Delta\beta$ can be expanded around $\omega_p/2$ in terms of the wave vectors of the interacting waves as:

$$\Delta\beta = (\beta_{TE} + \beta_{TM} + \beta_{QPM} - \beta_p) + (\beta_{TM}^{(1)} - \beta_{TE}^{(1)})\left(\frac{1}{2}\omega_p - \omega_s\right) + \frac{1}{2}(\beta_{TM}^{(2)} + \beta_{TE}^{(2)})\left(\frac{1}{2}\omega_p - \omega_s\right)^2 + \dots \quad (2)$$

Here, β_{TE} and β_{TM} are the propagation constants of the TE and TM polarized idler and input signal waves, and $\beta^{(n)}$ denotes the nth-derivative of the propagation constant with respect to angular frequency. Our waveguide design minimizes $\Delta\beta$ over an ultra-wide range of frequencies, achieving highly uniform gain of 22.4 dB over 334 nm band.

3. Waveguide design and performance

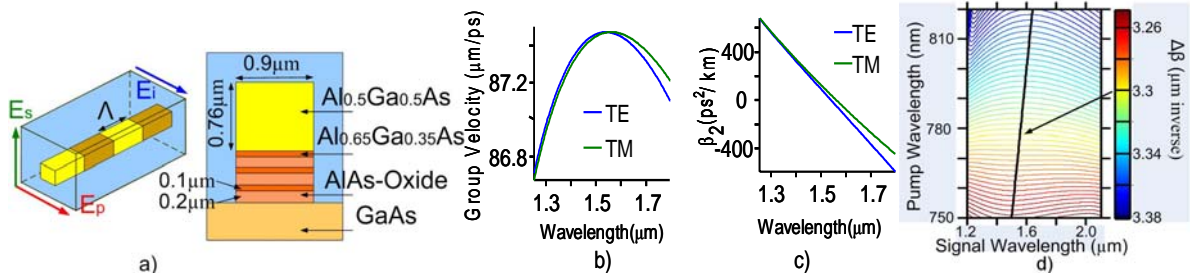


Figure 1. Waveguide (a) design, (b) $\beta^{(1)}$ parameter, (c) $\beta^{(2)}$ parameter, (d) $\Delta\beta$ for the designed waveguide.

The waveguide is designed for fabricating in the AlGaAs material platform grown on an orientation patterned GaAs template substrate realized by wafer-bonding [1]. Fig. 1(b) shows $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ core inside the polymer cladding [4]. The chromatic dispersion of AlGaAs material with varying aluminum content is modeled using the Sellmeier fit for the measured refractive index values [3]. Due to the high index contrast (56%) tight confinement is achieved, making the waveguide dispersion dominant and opposite in sign to the material dispersion. The optical isolation to the GaAs wafer is achieved by three alternating layers of $0.1\ \mu\text{m}$ thick $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ and $0.2\ \mu\text{m}$ thick oxidized AlAs material. The simulated wafer leakage and material loss, using FDTD software is $0.275\ \text{dB/cm}$. Due to fabrication inaccuracies, a more realistic loss level of $2\ \text{dB/cm}$ for pump signal and $1\ \text{dB/cm}$ for input signal is assumed. To achieve polarization insensitive operation, the waveguide is designed to be highly non-birefringent, meaning that the group velocities of the two polarizations are closely matched. Fig 2.(b) shows that $\beta^{(1)}$ parameter difference, proportional to the group velocity difference for TE and TM polarizations (second term in eq. 2) is minimized to $0.002\ \mu\text{m/ps}$. Average $\beta^{(2)}$ parameter for TE and TM polarizations (third term in eq. 2) is made zero around the signal wavelength, as shown in Fig. 2.(c). Now that higher order (frequency dependant) terms in eq. 2 are minimized or cancelled, $\Delta\beta$ does not depend on frequency, which is a crucial result that allows the high bandwidth of operation. To illustrate this, $\Delta\beta$ curves are presented in Fig. 2(d). For $\lambda_p=775\ \text{nm}$, $\Delta\beta$ is made constant across an ultra wide range of input signal frequencies, centered at $\lambda_s=1550\ \text{nm}$. Finally, once $\Delta\beta$ is made constant by the waveguide, QPM grating eliminates the first term of eq. 2. by introducing the constant correction $\beta_{QPM} = 2\pi/\Lambda$ and offsets $\Delta\beta$ to zero for all frequencies of interest. Here, Λ is the spatial period after which the interacting waves undergo a relative phase change of π radians, Fig. 1(a). Periodical reversing of the nonlinear susceptibility sign by reverting the crystal orientation ($\chi^{(2)}$ tensor direction) every Λ , Fig.1.(a), effectively re-phases the interaction [5]. Fig. 2.(e) also shows that the desired value is $\beta_{QPM}=3.3\ \mu\text{m}^{-1}$ (corresponding to the maximum flat $\Delta\beta$ curve) that, when introduced, gives $\Delta\beta\approx 0$, over the entire operating range, which was the initial task.

4. System results and discussion

Fig 2(a) illustrates the OPA using the DFG scheme. The pump (ω_p) is set at $775\ \text{nm}$, while the input signal (ω_s) is tuned across a range of frequencies in the $1550\ \text{nm}$ band. The output idler wave (ω_i) is generated at a frequency that is a ‘mirror image’ of the input signal frequency with respect to the half pump frequency ($\omega_p/2$). Assumed pump power is $17\ \text{mW}$. The device length is $20\ \text{mm}$.

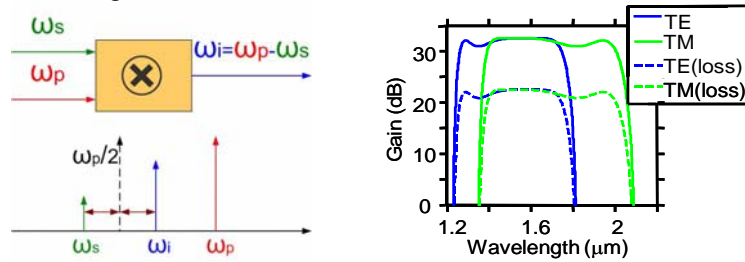


Figure 2. (a) Difference frequency generation map, and (b) parametric gain for lossy and no loss case.

The parametric gain is shown in Fig. 2(b) obtained by numerically solving the coupled wave equation system [6]. Highly uniform ($<0.5\ \text{dB}$ ripple) gain of $22.4\ \text{dB}$ is achieved over $334\ \text{nm}$ of common bandwidth (both polarizations overlapping). This is a key feature that makes the presented design polarization insensitive, a very important property for system applications. Another important attribute of the design is excellent gain uniformity, which will introduce only negligible distortion to the input signal, across the entire range of tuning. Finally, the demonstrated high gain is comparable to the gain of rare-earth-ion-doped amplifiers.

5. Conclusion

We have demonstrated a polarization insensitive waveguide design achieving highly uniform $22.4\ \text{dB}$ gain over $334\ \text{nm}$ band, with low pump power of $17\ \text{mW}$. Presented waveguide design is supported by the current fabrication capabilities in terms of growth thickness precision etching resolution and smoothness. The results exceed those previously reported [1], using the same material platform, by four orders of magnitude in gain and an order of magnitude in operating bandwidth.

6. References

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