Ultra strong parametric nonlinearities in AlGaAs-on-insulator waveguides

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Aluminum gallium arsenide has highly desirable properties for integrated parametric optical interactions: large material nonlinearities, maturely established nanoscopic structuring through epitaxial growth and lithography, and a large bandgap for broadband low-loss operation. However, its full potential for record-strength nonlinear interactions is only released when the semiconductor is embedded within a dielectric cladding to produce highly confining waveguides. From simulations of such, we present second and third order pair generation that could outperform state-of-the-art quantum optical sources and make novel regimes of strong parametric photon-photon nonlinearities accessible.

Entangled photons lie at the very heart of photonic quantum technology. The favored workhorse technique for their generation has long been spontaneous parametric down conversion (SPDC) from second order nonlinear crystals [1], due to their comparatively easy room-temperature operation, high spectral brightness, and ability to produce various forms of entanglement by setup design. For an efficient interaction, one must, however, carefully match the phase velocities of the pump and signal/idler fields (phase-matching) to compensate the dispersion of the nonlinear medium. Quasi-phase-matching (QPM) offers an elegant and efficient solution, but also restricts the type of crystal to be used for efficient photon pair sources to materials such as LiNbO$_3$, KTP or SLT, even when other materials would, in principle, offer significantly larger nonlinearities [2] or other beneficial functionalities.

Amongst the latter reside direct bandgap semiconductors with maturely established fabrication techniques that, hence, could enable highly efficient nonlinear devices with co-integrated pump sources. For possessing these features while also being compatible with telecom frequencies, aluminum gallium arsenide has been heralded as the “silicon of nonlinear optics” [3]. However, the low confinement that is commonly achieved in fabrication friendly (i.e. monolithic) phase matching approaches such as Bragg reflection waveguides (BRW) limits their performance [4–7]. Such structures typically feature efficiencies [8] on the order of $10^{-5}$ % $\text{cm}^{-3/2}$ which state-of-the-art lithium niobate based sources outperform significantly [9–12]. In contrast to this, fully surrounding the semiconductor core with dielectric cladding enables large index contrasts and highly tunable dispersion properties. In combination with sub-micrometer mode confinement, the effective nonlinearities of these structures increase drastically such that nonlinear processes can already become significant at very low levels of pump (seed) power. Such AlGaAs-on-insulator waveguides have recently been realized through flip-bonding the dielectric-capped AlGaAs layer onto a carrier substrate and enclosing the waveguide (WG) core in the same dielectric after its lithographic structuring. This has born impressive results in classical nonlinear optical interactions e.g. broadband Kerr frequency comb generation [13] as well as record efficiency on-chip second harmonic generation (SHG) - albeit for telecom-wavelength incompatible GaAs [14]. Furthermore, realizing parametric photon-photon nonlinearities has, in the past decade, become a distinct research effort of nonlinear quantum optics after numerous proposals have identified feasible strategies to lower seed power requirements towards single photon power levels [15–19]. The anticipated transformative advancement for scalable photonic quantum information processing that such interfaces would manifest continues to motivate an expanded quest of tailoring nonlinear platforms towards such functionality [20–24]. Our focus lies with the potential of AlGaAs-on-insulator to advance parametric nonlinearities to unprecedented regimes. We present WG-based sources of SPDC and four-wave mixing induced pair generation at (application friendly) telecom wavelengths and optimize their geometry for highest efficiency. In bulk architectures, the optical isotropy and the difficulty of fabricating QPM domains makes AlGaAs a less popular candidate for second order nonlinear processes [25,26]. Conveniently, any large refractive index material gains a significant optical birefringence when it is microscopically structured into highly confining WGs with asymmetric cross sections. Here, we propose thin film WGs (similar to those of [14]) for which the predominantly vertically polarized (TM$_{00}$-like) mode is designed to have the same refractive index at the pump frequency as the predominantly horizontally polarized (TE$_{00}$-like) signal/idler mode in the telecom C-band. In our simulations, an Al$_{x}$Ga$_{1-x}$As core ($x \geq 0.2$) is embedded in dielectric cladding (SiO$_2$) (see Fig. 1 insets). The cross-section of its rectangular core is varied until index matching is satisfied for a biphoton wavelength ($\lambda_0$) within the center of the C-band (1550 ±5 nm) [28]. The efficiencies for each phase-matched geometry are derived from the field distributions $\tilde{E}_m(\zeta,\xi)$ of the two modes ($m = \text{TE}, \text{TM}$) and the effective indices $n_m(\lambda)$ obtained through an Eigenmode analysis from a finite element solver. Explicitly, the biphoton lifetime $\tau$ (the inverse of the effective bandwidth) is calculated by integrating the phase...
Fig. 1. Waveguide dispersion of the horizontally and vertically polarized fundamental modes in an Al$_{0.3}$GaAs/SiO$_2$ waveguide. The strongly form-birefringent core geometry (108 x 1192 nm) features matching indices at the (biphoton) wavelength of 1551.4 nm and its corresponding second harmonic. The insets show the electric field distributions of the main polarization components of both modes at the phase matching wavelengths.

matching function:

$$\tau = \frac{1}{c} \int \left(1 - \frac{\lambda - \lambda_0}{\lambda_0}\right) \sin^2 \left(\frac{\Delta K(\lambda)L}{2}\right) d\lambda$$

(1)

where $L$ is the WG length and $\Delta K$ is the phase mismatch

$$\Delta K(\lambda) = 2\pi\left(\frac{n_{TM}(\lambda_0/2)}{\lambda_0/2} - \frac{n_{TE}(\lambda_0 - \lambda)}{\lambda_0 - \lambda} - \frac{n_{TE}(\lambda_0 + \lambda)}{\lambda_0 + \lambda}\right).$$

(2)

The simulated fields allow the derivation of the nonlinear overlap $\Gamma_d$ for which the fractional amplitudes in core and cladding weigh the average of the material susceptibilities $d_{\text{mat}}(\zeta, \xi)$. Due to the off-diagonal tensorial nature of the nonlinearity of AlGaAs ($d_{ijk} \neq 0 \iff i \neq j \neq k$), only the main polarization components of the two modes make a significant contribution to the three-field overlap [29]:

$$\Gamma_d = \frac{d_{\text{eff}}}{\sqrt{A_{\text{eff}}}} \approx \int \int E_{2\omega, TM}^* E_{\omega, TE}(\zeta, \xi) d\zeta d\xi$$

(3)

and the WG propagates in (110)-direction for a maximum projection of the TE-like mode on the cristallographic $ij$-axes. Because the linear power scaling of SPDC interacts with the quadratic scaling of second harmonic generation (SHG) when either interaction is pumped with the equivalent energy of one biphoton per lifetime [30]

$$P_{\text{spdc}} = P_{\text{shg}}(P_p = \frac{2hc}{\lambda_0\tau})$$

(4)

the SPDC efficiency follows from rearranging the equivalent expression for SHG, which is derived within the classical framework, accordingly

$$\eta_{\text{spdc}} = \frac{P_{\text{spdc}}}{P_p} = \frac{16\pi^2 h L^2 \Gamma_d^2}{\lambda_0^2 \varepsilon_0 n_{\text{eff}}^3 \tau} = \tilde{\eta}_{\text{spdc}} L^{3/2}.$$ 

(5)

Figure 2 shows the dispersion of the effective refractive index of the TE$_{00}$-like and TM$_{00}$-like mode in a 108 nm thick and 1192 nm wide Al$_{0.3}$GaAs core in SiO$_2$ cladding. Both effective indices are bound between the core and cladding material indices and phase matching is satisfied at the biphoton wavelength of $\lambda_0 = 1551.4$ nm. To find the optimum second order efficiency, we compare performance figures of five phase matched geometries with film thicknesses from 100 to 108 nm and corresponding widths from 875 to 1450 nm and an aluminum fraction of 20% with another set of five phase matched geometries with film thicknesses from 104 to 114 nm and corresponding widths from 966 to 2580 nm and 30% aluminum, respectively [31].

Figure 2 shows both efficiency distributions to feature the highest value at the center film thickness. The difference in the relative spread of width and thickness illustrates the sensitivity of the phase matching scheme towards the latter parameter. However, given the precise vertical control of epitaxial layers, a tradeoff towards insensitivity to the lithographically defined width is generally favorable. Furthermore, the softly peaked efficiency distributions ($\Delta\eta = 10\%$) over the applied geometric variations ($\Delta(t\cdot w) = 50\%$) implies an overall tolerance to parameter variance.

By comparison with experimentally-realized integrated sources, the proposed structures could improve down conversion efficiency by more than an order of magnitude. In BRW, for example, about $1.9 \cdot 10^{-5}$ %cm$^{-3/2}$ have been demonstrated [7], whereas WGs of periodically-poled lithium niobate yield efficiencies of about $1.2 - 2.4 \cdot 10^{-4}$ %cm$^{-3/2}$ [11][12]. Furthermore, the proposed WGs have potential for practical applications such as integrated sources for quantum key distribution. This is illustrated by the following estimate. The
peak efficiency corresponds to a spectral brightness of $\phi_\nu \approx 8.7 \cdot 10^6 \text{ (s mW GHz)}^{-1}$ (for a 1.7 nm long WG with a phase matching bandwidth of 35 nm). Assuming a temporal resolution of $\Delta t = 200$ ps, and trading-off double emission events, only 1 mW of overall pump power are required for producing 0.05 photon pairs per time bin per (55 GHz broad) dense wavelength division multiplexing channel. As such levels can be provided by simple laser diode structures, the on-chip integration of pump and SPDC source seems feasible from the standpoint of the optical power requirements.

Similar to the second order case, (Al)GaAs provides a large third order material nonlinearity to begin with and the effective nonlinearity is even more efficiently enhanced by mode confinement ($\gamma = 2\pi n_2/\lambda A_{\text{eff}}$). By virtue of this scaling, FWM schemes can reach efficiencies that allow for significant nonlinear optical interactions at single photon power levels. To also illustrate the potential of the AlGaAs-on-insulator platform for fundamental research applications, we expanded the simulations to yield the performance figures of so-called coherent photon conversion (CPC) schemes [15]. In our CPC implementation, a strong, red-detuned pump pulse is used to scale the coherent coupling of a photon pair at center frequency with an equally blue-detuned single photon seed (Fock pump).

Because of the high pump power, a phase shift from self- and crossphase modulation must be accounted for. The overall phase mismatch function becomes [19]

$$K(\omega) = \beta_2(\Omega^2 - \Delta^2) + \frac{\beta_4}{12}(\Omega^4 - \Delta^4) + \gamma P,$$

where $\Omega = \omega - \omega_0$ is the frequency variable of the Taylor expansion of the mode propagation constant ($\beta(\omega)$) about $\omega_0$ and $\Delta$ is the (fixed) detuning of either pump. Phase matching at center frequency is achieved by adjusting the peak power of the strong pump to

$$P_0 = \frac{1}{\gamma}(\beta_2\Delta^2 + \frac{\beta_4}{12}\Delta^4).$$

The signal idler bandwidth follows from integration

$$\Delta \omega_{\text{id}} = \int \sin^2\left(\frac{K(\omega)L}{2}\right) d\omega.$$  

The efficiency of converting the single photon pump into the signal idler pair is given by

$$\eta_{1\rightarrow2} = \eta L^{3/2}.$$

The flexibility of this nonlinear phase matching approach allows independent choice of core width and thickness. Accordingly, we scan over a two dimensional grid of WG cross sections to identify geometries with desirable dispersion properties - namely, a linear behavior of $n_{\text{eff}}(\lambda)$ around $\omega_0$ enables a large phase matching bandwidth and a large normal dispersion around $\omega = \omega_0 - \Delta$ suppresses spontaneous four wave mixing, see Fig. 3 for illustration. To further bridge the gap between the fundamental physics interest of testing the material platform to host single photon-level nonlinear interactons and the usefulness and practicality of such, we fix the wavelengths of the two pumps to 960 nm and 2060 nm such that the signal idler photon pair is centered in the telecom O-band (at 1310 nm). The choice of pump wavelengths accounts for the availability of single photon sources on the high energy side [32] and strong pump lasers on the low energy side (Thulium doped fiber lasers). Given these two pump wavelength regions, (aluminum-free) gallium arsenide is chosen as the core material because it offers both the largest material nonlinearity ($n_2 = 3.3 \cdot 10^{-17} \text{ m}^2 \text{W}^{-1}$) [33] and the largest index contrast to the SiO2 cladding while remaining free of one- and two-photon absorption, respectively.

The results of these scans are given in Figs. 4 and 5. A peak efficiency of 18 % cm$^{-3/2}$ is reached for the core geometry of 250×400 nm. This particular waveguide geometry provides extremely broadband phase matching with the signal idler photon pair spanning over the entire telecom O-band ($2\pi c \Delta \omega_{\text{id}} \omega_0^{-2} = \Delta \lambda_{\text{id}} \approx 128.9$ nm). The pump power required for phase matching the FWM process in this geometry amounts to $P_0(250 \times 400 \text{ nm}) \approx 948.0 \text{ W}$, which is well within reach of the peak powers that pulsed fiber lasers provide. The corresponding efficiency value of 18 % cm$^{-3/2}$ indicates that near-deterministic conversion with $\eta_{1\rightarrow2} \approx 1$ would require WGs of approximately 3 cm length. To satisfy the power dependent phase matching over several centimeters in linear waveguides, experimental loss rates that are currently on the order of 1 dB/cm for (Al)GaAs-on-insulator structures would need to be improved further. Alternatively, cavity-based approaches e.g. ring resonator cavities could circumvent the loss-induced scaling.
Fig. 4. Length-normalized CPC efficiency: a peak conversion efficiency of 18 % cm$^{-3/2}$ was found for the 250 $\times$ 400 nm GaAs core in 3 $\mu$m of SiO$_2$ cladding.

limitation. A back of the envelope calculation for the parameters of the 250 $\times$ 400 nm geometry substituted into [24]

\[
\eta_{1\leftrightarrow2} = \frac{256 R^2 \gamma^2 (\Delta \lambda_{FSR})^4}{\pi^2 \lambda^4} P_p \hbar \omega^2 Q^3 \left( \frac{Q}{Q^{ext}} \right)^4
\]

yields a conversion efficiency of $\eta_{1\leftrightarrow2} = 0.57$ % per resonance for a ring resonator of radius R = 50 $\mu$m with a (1dB/cm) loss-limited loaded quality factor of $Q = \frac{\pi \mu_0 n}{\alpha \lambda} \approx 260k$ at critical coupling. With the phase matching bandwidth of the 250 $\times$ 400 nm geometry spanning over one hundred free spectral ranges, pair generation of near-unity efficiency ($\tilde{\eta}_{1\rightarrow2} = \eta_{1\leftrightarrow2} \cdot \Delta \lambda_{si}/\Delta \lambda_{FSR} \gg 10\%$) would be approached so closely that the simplified interaction model that employs a classical seed field and neglects its depletion breaks down. Studying this regime of strong photon-photon nonlinearities both experimentally and theoretically could elucidate novel quantum optical phenomena.

We have demonstrated flexible phase matching schemes for second and third order nonlinear interactions at telecom wavelengths on the (Al)GaAs-on-insulator material platform. In both cases, we scanned over geometric variations that were large enough to identify peak efficiency waveguide models. With a required pump power of only 1 mW for key-rate optimized photon pair generation throughout the entire C-band, the suggested structures could outperform state-of-the-art lithium niobate based QKD-sources by an order of magnitude. Finally, the simulated CPC efficiencies are evidence that parametric nonlinear interactions can be tailored to already become significant at single photon (seed) power level. As a host to this virtue, the presented waveguide models could uncover novel quantum optical phenomena of strong photon-photon nonlinearities.

Fig. 5. Phase matching bandwidths corresponding to the calculated efficiencies: broadband biphotons that span over the entire telecom O-band are found for several core geometries. The bandwidth calculated for the 250 $\times$ 400 nm core results to 128.9 nm.

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DISCLOSURES

The authors declare no conflicts of interest.

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