Difference-frequency generation in an AlGaAs Bragg-reflection waveguide using an on-chip electrically-pumped quantum dot laser

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Nonlinear frequency conversion is ubiquitous in laser engineering and quantum information technology. A long-standing goal in photonics is to integrate on-chip semiconductor laser sources with nonlinear optical components. Engineering waveguide lasers with spectra that phase-match to nonlinear processes on the same device is a formidable challenge. Here, we demonstrate difference-frequency generation in an AlGaAs Bragg reflection waveguide which incorporates the gain medium for the pump laser in its core. We include quantum dot layers in the AlGaAs waveguide that generate electrically driven laser light at ∼790 nm, and engineer the structure to facilitate nonlinear processes at this wavelength. We perform difference-frequency generation between 1540 nm and 1630 nm using the on-chip laser, which is enabled by the broad modal phase-matching of the AlGaAs waveguide, and measure normalized conversion efficiencies up to (0.64 ± 0.21) %/W/cm². Our work demonstrates a pathway towards devices that utilize on-chip active elements and strong optical nonlinearities to enable highly integrated photonic systems-on-chip.

Second-order (χ(2)) nonlinear optical processes [1–2] have been widely utilized in quantum computation, communication and metrology [3–11]. In addition, second-harmonic, difference-frequency (DFG) and sum-frequency generation, can be used to prepare and measure ultrafast laser pulses [12–13], erase spectral distinguishability between single photon emitters [14] and engineer lasers at otherwise hard-to-reach wavelengths [13]. Today, most χ(2) photonic devices rely on crystals such as BaB₂O₄, LiNbO₃ or KTiOPO₄ that exhibit high nonlinear conversion efficiencies, but are limited in scalability as they cannot directly host active optical components such as lasers and photodetectors.

Photonic circuits in the direct band-gap semiconductor AlGaAs enable integration of active components on a platform with strong χ(2) nonlinearity. Significant effort has been committed to develop miniaturized, on-chip AlGaAs devices with increasing complexity and richer applications [16–18]. In particular, AlGaAs Bragg-reflection waveguides (BRWs) facilitate phase-matching in the telecom band and exhibit strong mode confinement, which has led to large nonlinear conversion efficiencies up to 2.5 · 10⁻² %/W/cm² for DFG [19]. Simple waveguide circuits [20], entangled photon pair sources [21,22], single photon emitters [23] and on-chip lasers [24] have been demonstrated with BRWs. However, there has been limited development of devices that exploit active components, such as lasers, and the strong second order nonlinearity at the same time [25–26]. Recent work demonstrates DFG conversion efficiency of up to 169 %/W/cm² by utilizing an internal quantum well laser [27].

In our approach, we demonstrate an AlGaAs BRW with an embedded Al₀.13In₀.47Ga₀.44As quantum dot (QD) laser. This material composition enables the laser to emit at a wavelength around 790 nm at room temperature and increases the gain in comparison to conventional InGaAs QDs [28–29]. The device is engineered such that the higher-order Bragg mode phase-matches at this wavelength with the fundamental total internal reflection (TIR) mode in the telecom band. The nonlinear waveguide comprises the active gain medium in an edge-emitting cavity, forming our electrically driven pump laser. We determine the threshold current of the internal laser and use the chip temperature to tune its spectral properties, such that it pumps type-2 nonlinear processes. By injecting a telecom signal laser into the waveguide, we generate an additional telecom idler field via DFG. We reconstruct the joint spectral intensity (JSI) by spectrally resolving the generated idler field, and extract a nonlinear conversion efficiency of up to (0.64 ± 0.21) %/W/cm². While this is a clear improvement in comparison to previously reported BRWs without internal laser (passive structures), the device requires further engineering to match the results in Ref. [27].

We fabricate our BRWs starting with an epitaxially grown AlₓGa₁₋ₓAs stack with varying aluminum concentrations x and layer thicknesses [30]. We subsequently pattern waveguides by electron beam lithography and dry etching in Ar and Cl₂ plasma. In this work, we utilize a 1.48 mm long and 3.5 µm wide waveguide sample with an etch depth of about 4.6 µm. A schematic is depicted in Fig. 1. The waveguide geometry is designed for tight...
Quantum Dots: 43% Al, 174/190 nm
Core: 17% Al, 27 nm
Quantum Wells: 17% Al, 27 nm
Quantum Dots: 13% Al, 47% In

FIG. 1. Schematic of the waveguide cross section. The QD layers are embedded within quantum wells with a total thickness of 27 nm, which are centered in the core. The thicknesses have been measured via scanning electron microscopy and the layers on top of the core (first value) differ slightly from the ones underneath (second value). The structure is doped in the capping layer (20 · 10^18 cm⁻³), the Bragg mirrors (2 · 10^18 cm⁻³) and the matching layers (1 · 10^18 cm⁻³) farther from and 0.5 · 10^18 cm⁻³ closer to the core) with C and Si atoms, respectively.

Confinement of the Bragg and TIR modes and this leads to a simulated effective nonlinearity of $\Delta n_{\text{eff}} = 56 \text{ pm}/\text{V}$ (see Supplementary Section 1). The device is planarized with Benzocyclobuthene (BCB) to allow for depositing electrical contact pads larger than the waveguide width. The layer structure enables modal phase-matching between the TIR mode at ~1580 nm confined to the core and matching layers, and higher order Bragg modes at ~790 nm confined by the Bragg-mirror stacks [30, 31]. Two quantum dot layers are embedded at the center of the waveguide core and are surrounded by Al₀.₁₇Ga₀.₈₃As quantum wells to increase carrier accumulation. We dope the upper and lower mirror stacks as well as the substrate with carbon and silicon atoms to create a p-i-n junction. The mechanically cleaved waveguide facets have ~32% reflectivity and form a cavity surrounding the gain medium. The QD dipoles are oriented to emit horizontally polarized light into the Bragg mode.

We use a pulsed voltage supply to characterize the QD laser with 0.4% duty cycle (8 kHz repetition rate, 500 ns pulse width) to reduce the thermal load on the sample while still achieving peak currents above the lasing threshold. This is necessary, as parts of the gold layer are too thin to withstand the electrical power necessary for continuous wave lasing (see Supplementary Section 2). We increase the peak voltage of the pulse generator and measure the current and generated optical power. This way, we determine the lasing threshold of (618 ± 4) mA, which corresponds to a current density of (11.9 ± 0.5) kA/cm², as can be seen in Fig. 2. The insets depict the spectrum of the laser below and above the threshold current, respectively. This result of the lasing threshold is comparable to similar integrated lasers in BRWs [25]. However, optimized structures can offer significantly lower lasing thresholds down to a few tens of milliamperes [24, 27].

In addition to the introduction of an internal QD laser, we engineer our BRWs to enable second-order nonlinear optical processes. The frequency conversion obeys energy and momentum conservation

$$\omega_p = \omega_s + \omega_i,$$

$$k_p(\omega_p) = k_s(\omega_s) + k_i(\omega_i),$$

where $\omega_j$ and $k_j(\omega_j) = n_j \omega_j / c$ are the frequency and wavenumber with $j \in \{p, s, i\}$ corresponding to pump, signal and idler and $c$ is the speed of light. The wavenumbers are directly proportional to the effective refractive indices $n_j$ of the corresponding modes. Thus, we engineer the waveguide geometry to yield matched effective refractive indices at the desired wavelengths [32].

We characterize the phase-matching by measuring the laser spectrum and second harmonic generation while tuning the temperature (see Supplementary Sections 3 & 4). Due to the resulting change in the material bandgap and refractive index, the central wavelength of the laser can be shifted. This way, we determine a working point at 3.5°C and 792.9 nm for the pump laser, at which we can investigate DFG.

We utilize the setup shown in Fig. 3(h), where we use a half-wave plate and a polarizer to control the power and polarization of the seed laser, which is coupled into the waveguide with a 100× microscope objective. The generated idler photons are then collected with a 0.68 NA aspheric lens and coupled to a spectrometer with a high-sensitivity InGaAs CCD. We use polarization, longpass, and bandpass filters to suppress the pump and seed lasers.

We characterize the DFG process with the telecom seed laser set to 1614.0 nm and a normalized power of 909 µW. By turning on the internal QD laser as the pump, we stim-
FIG. 3. a) Experimental setup for performing difference frequency generation. The seed laser is coupled to the waveguide using a microscope objective. After the waveguide, we suppress the pump via a 1400 nm longpass filter and the seed laser via polarization control (consisting of a half-wave plate, a quarter-wave plate, a polarizer and a polarizing beam splitter), as well as a 40 nm bandpass filter centered at 1550 nm. The remaining light is coupled into a single mode fiber and analyzed with a spectrometer and an InGaAs camera.

b) Example for the measured DFG spectrum at a seed wavelength of 1614 nm and a pump wavelength of 792.9 nm for the quantum dot laser. Here, the seed laser is set to 1614 nm and the corresponding DFG signal is centered around 1558 nm. c) Joint spectral intensity reconstructed via DFG. At the regions marked with a white box, no signal could be measured due to insufficient filtering (dashed). d) Dependency of the DFG signal on the seed laser power and the corresponding slope $b$. The data represents the mean values, and the error bars the corresponding standard error of mean for an integration time of 300 s.

ulate the corresponding DFG idler emission at 1558 nm as can be seen in Fig. 3(b). We tune the seed laser wavelength from 1530 nm to 1640 nm to measure the JSI – the correlation of signal (seed) and idler (DFG) wavelengths – which is enabled by the broad phase-matching of the BRW. The resulting JSI is shown in Figs. 3(c). Close to degeneracy ($\lambda_s \approx \lambda_i$), the bandpass filter can no longer suppress the seed and we therefore cannot record the DFG spectrum, as the laser oversaturates the detector. Narrow bandwidth filters at different central wavelengths would be necessary to measure the DFG in this region. Thus, we potentially miss the highest conversion efficiency, as our samples are designed for degeneracy.

Finally, we investigate the nonlinear conversion efficiency of our BRWs. We use the same settings as before, but fix the seed laser wavelength while tuning its power. This way, we measure the power dependency of the integrated DFG spectrum, as shown in Fig. 3(d). By adding a linear fit, we extract the slope $b$ in units of Hz/mW and the offset, which corresponds to the constant background (i.e. photoluminescence, dark counts and stray light). Note that we have chosen to tune the seed power since photoluminescent background light is not promoted by telecom wavelengths and is thus a constant in our measurement [33]. We determine the conversion efficiency

$$\eta_{\text{conv}} = \frac{1}{\eta P_i P_s L^2} \frac{P_i}{P_s} = \frac{b E_\gamma}{\eta P_s L^2},$$

(3)

where $P_p$, $P_s$ and $P_i$ are the normalized powers of the pump, signal and idler beams within the device (see Supplementary Section 5), respectively. The waveguide length is $L = 1.48$ mm and $E_\gamma$ is the energy of the frequency converted photons. We normalize the result for the total loss in our experimental setup $\eta = (-56.7 \pm 0.7)$ dB for telecom light (see Supplementary Section 6). The normalized internal QD laser power is set to $P_p = 2.436 \mu$W and we thus extract a conversion efficiency of $(0.64 \pm 0.21)\%$/W/cm$^2$. For comparison, we perform DFG in the same waveguide using an externally coupled pump laser and present the results in Table 1 (more results can be found in Supplementary Section 7).

As these results are fully normalized, we expect the
We expect that optimization of the device [30] could increase the conversion efficiency by at least an order of magnitude. Furthermore, the losses within our active waveguide of −4.458 dB/mm for telecom light are much higher than typical values in our passive waveguides of about −2 dB/mm. These additional losses are caused by the QDs and doping of the sample. In addition, adding a reflective coating to the waveguide facets would improve the laser cavity and decrease the lasing threshold. Combined with thicker gold contacts, this could enable DC pumping.

In conclusion, we have demonstrated an integrated QD laser embedded in an AlGaAs BRW structure. By controlling the temperature of the chip, the internal laser wavelength can reach the nonlinear phase-matching condition, allowing for electrically pumped nonlinear processes. We have determined the nonlinear conversion efficiency of this sample via DFG, and made a comparison by externally pumping the process in this device and a passive structure. Even though our BRW does not reach a conversion efficiency as high as in devices based on a quantum well laser [27], a comparison with our passive structures shows the potential for improvement. In principal, QD lasers allow for a lower threshold current [35], a higher spectral range and a large modulation bandwidth in comparison to quantum wells systems [36]. This flexibility can be important for advanced integrated photonic circuits. Furthermore, the tighter confinement of the modes in our device leads to a higher simulated effective nonlinearity of \( d_{eff} = 56 \text{ pm/V} \). Since DFG uses the same principle and nonlinear effects as SPDC our work presented here marks another step towards fully integrated active and nonlinear photonic circuits.

### DATA ACCESS STATEMENT

The data that support the findings of this study are openly available at the following DOI: [https://doi.org/10.5281/zenodo.4737162](https://doi.org/10.5281/zenodo.4737162)

### AUTHOR CONTRIBUTIONS

Conceptualization, A.S., R.J.C., S.F., G.W.; Formal analysis, A.S., M.G.; Methodology, A.S., R.J.C., S.F.; Investigation, A.S., M.G.; Resources, H.T., H.S., M.K., S.H., C.S.; Software, A.S., M.G., R.J.C.; Supervision, R.J.C., S.F., G.W.; Writing - original draft, A.S., R.J.C.; Writing - review & editing, All Authors; Funding acquisition, C.S., G.W.;

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| type                 | normalized power | \( \lambda_0 \) (nm) | \( \lambda_i \) (nm) | \( \lambda_t \) (nm) | \( b \) (Hz/mW) | \( \eta_{conv} \)%(%/W/cm²) |
|---------------------|------------------|----------------------|----------------------|----------------------|----------------|----------------------------|
| internal laser      | 2.436 µW         | 792.9                | 1626                 | 1548                 | 5.70 ± 1.55   | 0.64 ± 0.21               |
| external laser      | 2.687 mW         | 792.9                | 1619                 | 1554                 | 409 ± 8        | 0.041 ± 0.006             |
| passive sample      | 2.88 mW          | 767.3                | 1510                 | 1560                 | (12.34 ± 0.02) · 10³ | 0.72 ± 0.12               |

TABLE I. Highest measured conversion efficiencies for different measurement settings, using the external and internal laser.
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