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Quasi-Phase-Matched Difference Frequency Generation at 3.4 μm in High-Quality GaAs/AlGaAs Waveguides

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1. Introduction

Tunable coherent mid-infrared (MIR) light sources are useful in various spectroscopic applications such as gas sensing. Difference frequency generation (DFG) offers a way to generate high-quality MIR coherent radiation by mixing near-infrared laser lights. Quasi-phase-matched (QPM) DFG of MIR radiation in 2–5 μm wavelength region has been demonstrated in periodically-poled $LiNbO_3$ (PPLN) waveguides. A normalized conversion efficiency of 40 %/W was achieved at 3.2 μm in a 50-mm-lomg QPM PPLN waveguide [1]. Much more efficient wavelength conversion is expected in GaAs-based QPM devices because of its large quadratic optical nonlinearity (compare d_{14}(GaAs) = 90 pm/V with d_{33}($LiNbO_3$) = 25 pm/V). Furthermore, since GaAs is transparent down to about 17 μm, they can be used in QPM DFG devices operating in a wide MIR wavelength range. Although a bulk GaAs QPM DFG device operating at 8 μm has been reported [2], its conversion efficiency is quite low (< 10^{-2} %/W in a 19-mm-long QPM GaAs) owing to the lack of the tight light confinements in the bulk device. In this paper, we report MIR QPM DFG in high-quality periodically-inverted GaAs/AlGaAs waveguides.

2. Dvice Fabrication

We fabricated periodically-inverted GaAs/AlGaAs QPM DFG ridge waveguides that mix 1.064 μm pump and 1.55 μm signal lights to generate 3.4 μm idler output. The QPM waveguide consists of a 1.6-μm-thick GaAs guiding layer sandwiched between a 1.0-μm-thick $Al_{0.1}Ga_{0.9}As$ overcladding and 7.0-μm-thick $Al_{0.1}Ga_{0.9}As$ undercladding layers. A 5-μm-wide ridge is formed by etching the overcladding layer by 0.9 μm in depth. The QPM period for DFG is 7.8 μm. We fabricated the periodically-inverted GaAs/AlGaAs waveguide using sublattice reversal epitaxy technique [3,4]. Details of the fabrication process are described in ref. [5]. We paid special attention to the regrowth process forming GaAs/AlGaAs waveguiding structure on the planarized periodically-inverted template. In order to suppress corrugation formed on the core/clad interfaces and overcladding surface due to the anisotropic diffusion of Ga atoms on GaAs (100) surfaces [6], we performed molecular-beam epitaxy (MBE) regrowth under a low-temperature condition (430°C throughout the $Al_{0.1}Ga_{0.9}As$ MBE regrowth).

Figure 1(a) shows a SEM photograph of a stain-etched cross section of the fabricated GaAs/AlGaAs waveguide and Fig. 1(b) shows an AFM image of the surface of the fabricated waveguide. The height of the surface corrugations is less than 20 nm which is the smallest value we have achieved to date.

(a)

(b)

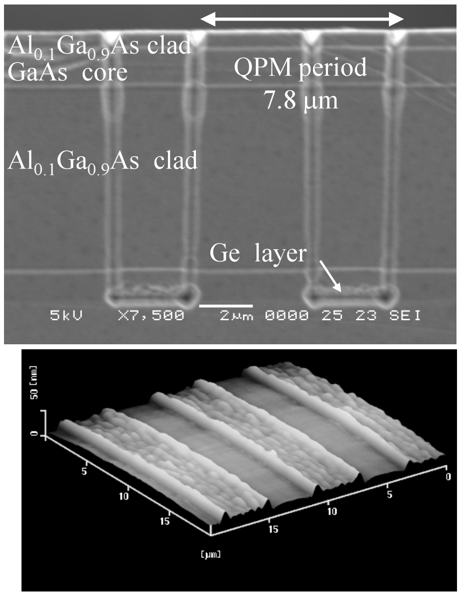

Fig. 1: (a) SEM image of a stain-etched cross section of the fabricated GaAs/AlGaAs waveguiding devices. (b) AFM image of the surface of the fabricated device.

3. Characterization

We measured propagation loss of the fabricated QPM ridge waveguide by using the Fabry-Perot method and obtained 2.3 dB/cm at 1.55 μm. To the best of our knowledge, this is the lowest propagation loss reported in periodically-inverted GaAs/AlGaAs waveguides.

We characterized wavelength conversion performance of the fabricated device by DFG at room temperature. We used a cw Nd:YAG laser oscillating at 1.064 μm and a tunable external-cavity GaInAsP laser operating in 1.52–1.57 μm as a pump and a signal input light sources, respectively. TM-polarized pump and TE-polarized signal lightwaves are combined using a polarizing beamsplitter and fed into a 4.93-mm-long QPM GaAs/AlGaAs waveguide by end-fire coupling. Generated TE-polarized DFG output was detected using an InSb photodetecter. We measured the phase-matching characteristic of the device by scanning the wavelength of the signal input light. The obtained tuning curve is shown in Fig. 2(a). 1st-order QPM in DFG is achieved at 1.558 μm (corresponding DFG wavelength is 3.356 μm). The observed tuning curve closely agrees with theoretical one calculated using the physical device length L = 4.93 mm. This clearly demonstrates the excellent uniformity of the fabricated waveguide. Shortperiod oscillation superimposed on the standard sinc-squared tuning curve is due to the Fabry-Perot interference of the signal light wave. Clear interference fringes indicate relatively low propagation losses and accuracy of the experiments.

We measured the output DFG power as a function of input signal power while the pump power was kept constant, as shown in Fig. 2(b). As expected, the DFG power is linearly proportional to the product of the pump and signal powers. For a few mW of pump and signal power, detected DFG power was a μW-level. The estimated conversion efficiency is over three orders of magnitudes larger than that of bulk QPM GaAs and comparable to the several-cm long best PPLN waveguiding devices.

Temperature tunability was characterized by measuring signal peak wavelengths of parametric fluorescence dependent on the temperature of the waveguide. Figure 3 shows optical parametric fluorescence temperature tuning curve of the GaAs/AlGaAs waveguide. The obtained experimental data are in reasonable agreement with theoretical tuning curves. Obtained temperature tuning rates are –1.0 nm/K for signal in 1.55 μm range and 4.0 nm/K for idler in 3.4 μm range, respectively. A 240 nm-wide tunability for idler can be achieved by changing temperature of the waveguide from 300 K to 360 K.

4. Conclusion

We have fabricated high-quality periodically-inverted GaAs/AlGaAs ridge waveguides and characterized their DFG performance. By introducing the low-temperature MBE process for growing GaAs/AlGaAs waveguiding structures, we have succeeded in fabricating waveguides with small corrugations (< 20 nm) on their interfaces and surfaces. The measures propagation loss was quit low (2.3 dB/cm at 1.55 μm), and the estimated DFG efficiency was reasonably high. The obtained temperature tuning rate was 4.0 nm/K for idler in 3.4 μm range. Without doubt, these results will lead to highly efficient and widely tunable MIR light sources based on the DFG in QPM GaAs waveguides.

Acknowledgments

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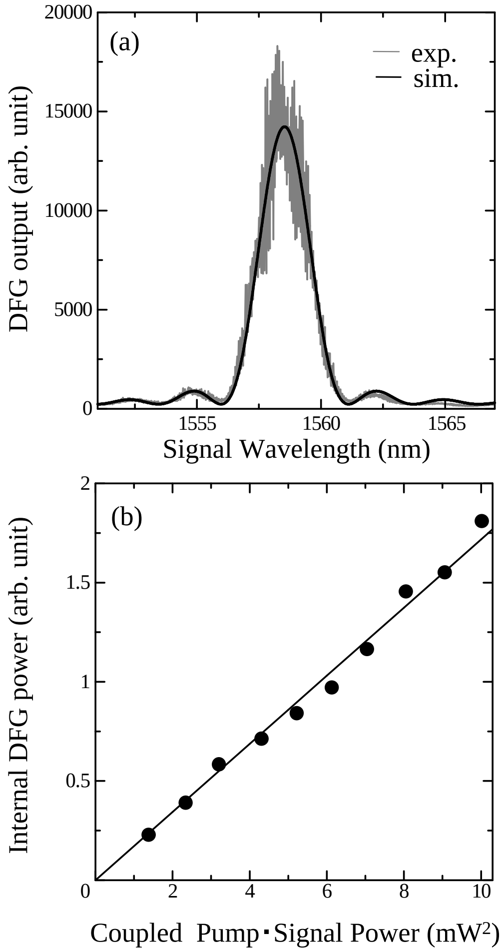

Fig. 2: (a) DFG tuning curve of a 4.93-mm-long QPM GaAs/AlGaAs waveguide. (b) DFG internal output power vs the product of the input pump and signal powers.

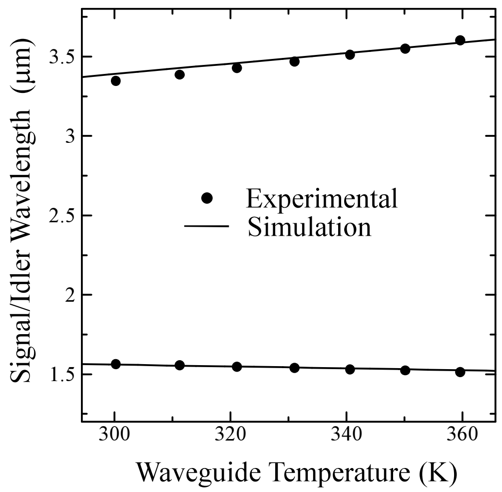

Fig. 3: Temperature tuning curves of the GaAs/AlGaAs waveguide device.