Design and Simulation of 450 nm GaN-based Multiple-quantum-well Tunable V-cavity Laser

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Abstract— We present the design and simulation of a 450 nm GaN-based V-cavity tunable laser without grating and epitaxial regrowth. Quantum well structure has been optimized to realize good optical confinement. The simulation results show that 20 channels with 300 GHz spacing can be achieved, with a tuning range of 4.1 nm and high high side-mode suppression ratio (SMSR) over 30 dB.

1. INTRODUCTION

Tunable blue laser diodes based on gallium nitride (GaN) are of great interest for high resolution spectroscopy, such as gas analysis [1], industrial process monitoring [2], and combustion diagnostics [3], and bio-medical analysis. At present, GaN-based blue light sources are mainly on light emitting diodes (LED) or multimode Fabry-Perot lasers, which has poor spectral identity and tunability. Tunable blue laser diodes based on external cavity grating structure has recently been reported with narrow linewidth and wide tunable range [4–6], but it requires precise mechanics and alignment, complex structure, bulky and expensive systems. While for monolithic GaN laser, the complex gratings such as SG-DBRs used in telecom tunable lasers is difficult to fabricate for blue light, because the period of the gratings needed for blue light is too small. Recently, a compact tunable V-cavity laser (VCL) was proposed and wavelength tuning of up to 50 channels with 100 GHz spacing around 1550 nm was demonstrated experimentally with excellent side-mode suppression ratio (SMSR) in InP based material system [7]. Unlike those grating based tunable lasers, the longitudinal mode selection mechanism of the V-cavity laser has no limitation of such small period. By emplying this V-cavity laser structure, we designed a compact GaN-based V-cavity tunable laser with wide tuning range.

2. DEVICE DESIGN AND SIMULATION

Figure 1(a) shows the schematic diagram of a V cavity laser. It consists of a fixed gain cavity and a channel selector cavity with different optical path lengths, which are coupled through a 2×2 half-wave coupler.The half-wave coupler has been discussed in [8]. Since backside contacts are not available with the sapphire substrate, the device geometry is designed to use coplanar electrodes with shallow etched waveguide and deep etched mesa. Three positive electrodes and one negative electrodes are used. The coupler electrode is used for providing gain and small phase adjustment. In order to achieve good single mode operation and wide range tuning, the Vernier effect is used between the two cavities. The cross-section layer structure is shown in Figure 1(b). The active region consists of a three period MQW with 3 nm $In_{0.2}Ga_{0.8}N$ well and 15 nm GaN barrier. Since the mobility of electrons are much higher than holes, a typical 15 nm electron blocking layer (EBL)

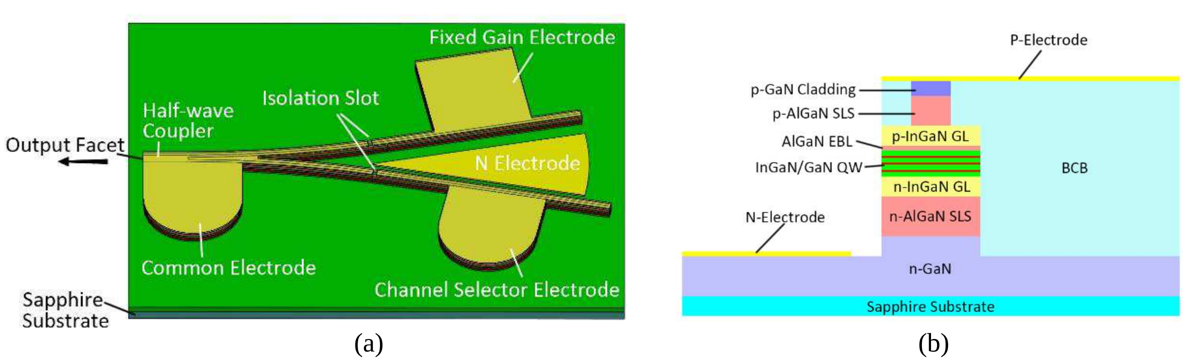


Figure 1: (a) Schematic diagram of a V cavity laser and (b) its layer structure.

of $Al_{0.2}Ga_{0.8}N$ is used to prevent the electrons from flowing into the p-type region. For nonpolar or semi-polar GaN laser diodes, high Al composition cladding layers are often used for large optical confinement, which causes macroscopic cracking [9]. It also brings some further drawbacks from the material perspective as discussed in [10]. Therefore, we adopt multiple periods of 2 nm/2 nm $Al_{0.3}Ga_{0.7}N$/GaN superlattice structure (SLS) layer, and use relatively high indium composition guiding layers (GLs) to realize high confinement factor. The thicknesses of the p-SLS and n-SLS layers are 400 nm and 600 nm respectively.

Figure 2(a) shows the vertical optical mode and refractive index profile along the growth direction of the layer structure, which was calculated by transfer matrix method (TMM) [11]. Large confinement factor $\Gamma(= 0.1813)$ is realized with high indium content InGaN GLs and high aluminum content AlGaN/GaN SLSs. The low reflective index of p-AlGaN EBL shifts the peak of the optical mode from the center of the active region toward the n-side layers, which results in asymmetric mode profiles and slightly lower [12]. Figure 2(b) shows that a slight resonance of the waveguide mode appears in the n-GaN layer which forms a resonator between the n-SLS and the substrate. It can be reduced by increasing the thickness or aluminum content of the n-SLS, which will also cause macroscopic cracking from the processing perspective. There is therefore a trade-off between high optical confinement and processing tradition. Figure 2(c) shows the dependence of optical confinement factor Γ on the indium composition of the InGaNGLs for different aluminum composition of the AlGaN/GaN SLSs. Γ increases as the indium composition in the GLs and aluminum composition in SLSs increases. Higher indium and aluminum content leads to a larger refractive index difference Δn between the GLs and SLS cladding layers, which results in a higher Γ. At low indium composition, there is insufficient confinement for $Al_{0.05}Ga_{0.95}N$ and $Al_{0.1}Ga_{0.9}N$ SLS layer structure. Γ increases to saturation when indium composition is greater than 0.04. When aluminum composition of SLS layer reaches 0.15, the SLS layer itself can get enough Δn to confine the optical mode in active region even with low indium composition guiding layer.

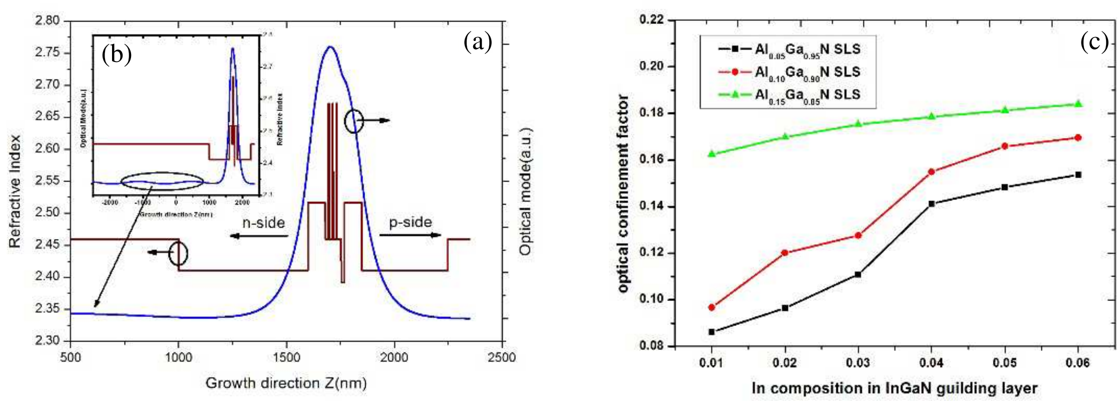


Figure 2: (a) Optical mode profile and refractive index on the growth direction Z of the layer structure and (b) anti-guide behavior of the n-GaN layer, (c) confinement factor (Γ) of various SLS structures versus In composition of the InGaN GLs.

Detailed theory, design principle and numerical results of the V-coupled cavity laser based on InP material system has been described in [8]. The device based on GaN was simulated using the same method. We set the length of the fixed gain cavity to 200 μm and calculated the threshold gain, SMSR and free spectral range (FSR) for GaN-based VCL with 2.5%, 5%, 10%, 15% cavity length difference, respectively. The switchable wavelength range is greatly increased by using Vernier effect, where the FSR of the combined cavity is determined by

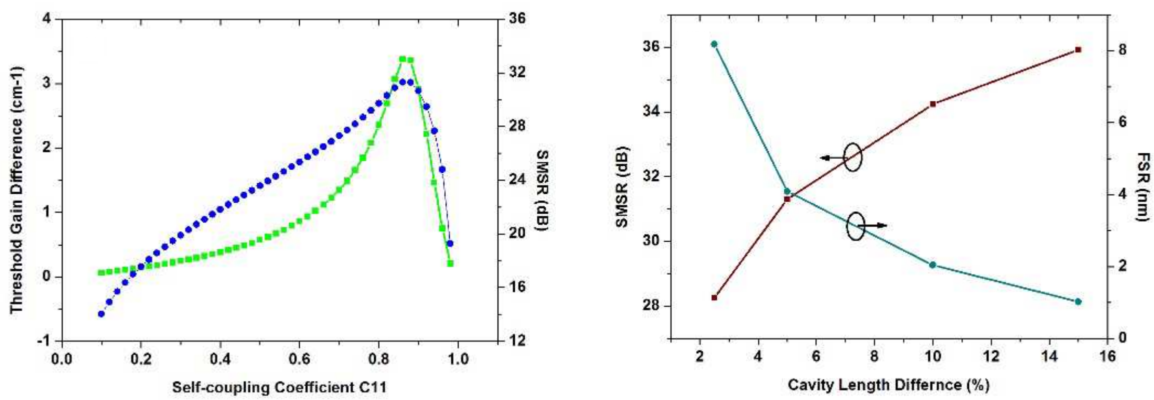
$$\Delta f_c = \frac{\Delta f \Delta f'}{|\Delta f - \Delta f'|} \tag{1}$$

where Δf and $\Delta f'$ are the resonance frequency interval for the fixed gain cavity and channel selector cavity, respectively. We define bar-coupling coefficient as C_{11} and cross-coupling coefficients as C_{21}, and they have a relative phase difference $\phi = m\pi$ ($m = 0, \pm 1, \ldots$) between them. For optimal operation of the V-coupled cavity laser, half-wave coupler should satisfy $|C_{11}| + |C_{21}| = 1$. The threshold gain (in intensity) ΔG can be calculated by

$$\Delta G = -10\log_{10}\left(|C_{11}|^2 + |C_{21}|^2 + 2|C_{11}|\,|C_{21}|\cos\phi\right)/(8.686L). \quad (2)$$

and SMSR is calculated using the equation in [13].

Figure 3(a) shows the threshold gain difference and corresponding SMSR as a function of the bar-coupling coefficient C_{11} for a cavity length difference of 5%, maximal SMSR of 31.3 dB is obtained with the corresponding threshold gain difference among the longitudinal modes is 3.38 cm^{-1}. Figure 3(b) shows the variations of SMSR and FSR versus the cavity length difference, we can see that the SMSR increases with the cavity length difference while FSR decreases with it, so we have to trade-off between these two factors.



(a) (b)

Figure 3: (a) Threshold gain difference and corresponding SMSR as a function of the self-coupling coefficient for a cavity length difference of 5%, (b) variations of SMSR and FSR versus the cavity length difference between fixed gain cavity and channel selector cavity.

Since the SMSR greater than 30 dB is acceptable for GaN laser diodes, to get a broader FSR we choose 5% cavity length difference, which can realize an FSR of 4.09 nm, or ~ 6 THz. The channel spacing can be calculated by $\Delta f = c/(2n_gL)$, which corresponds to 300 GHz. Therefore, we can obtain about 20 channels within an FSR.

3. CONCLUSIONS

In conclusion, we have presented the design and simulation of a GaN-based MQW tunable V-cavity laser with a reflective 2×2 half-wave optical coupler. Vertical optical mode profile are calculated by TMM method. With considering the material properties and processing conditions, we obtain large confinement factor $\Gamma(= 0.1813)$ with relative high indium doped InGaN GLs and aluminum doped AlGaN SLSs. Threshold gain, SMSR and FSR are also calculated for different structural parameters. With 5% cavity length difference, 20 channels with 300 GHz spacing within the free spectral range of 4.1 nm and high SMSR over 30 dB are achieved.

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REFERENCES

1. Werle, P. W., P. Mazzinghi, F. D'Amato, M. De Rosa, K. Maurer, and F. Slemr, "Signal processing and calibration procedures for in situ diode-laser absorption spectroscopy," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, Vol. 60, No. 8, 1685–1705, 2004.
2. Schlosser, E., J. Wolfrum, L. Hildebrandt, H. Seifert, B. Oser, and V. Ebert, "Diode laser based in-situ detection of alkali atoms: Development of a new method for determination of residence-time distribution in combustion plants," *Appl. Phys. B*, Vol. 75, No. 2–3, 237–247, 2002.

3. Allen, M. G., "Diode laser absorption sensors for gas-dynamic and combustion flows," *Meas. Sci. Technol.*, Vol. 9, No. 4, 545–562, 1998.
4. Hult, J., I. S. Burns, and C. F. Kaminski, "Wide-bandwidth mode-hop-free tuning of extended-cavity GaN diode lasers," *Applied Optics*, Vol. 44, No. 18, 3675–3685, 2005.
5. Komorowska, K., et al., "Tunable broad-area InGaN laser diodes in external cavity," *Integrated Optoelectronic Devices*, International Society for Optics and Photonics, 2007.
6. Omori, M., N. Mori, and N. Dejima, "Tunable light source with GaN-based violet laser diode," *SPIE OPTO*, International Society for Optics and Photonics, 2013.
7. Zhang, S., et al., "Simple and compact V-cavity semiconductor laser with 50×100 GHz wavelength tuning," *Optics Express*, Vol. 21, No. 11, 13564–13571, 2013.
8. He, J. J. and D. Liu, "Wavelength switchable semiconductor laser using half-wave V-coupled cavities," *Optics Express*, Vol. 16, No. 6, 3896–3911, 2008.
9. Okamoto, K., et al., "Pure blue laser diodes based on nonpolar m-plane gallium nitride with InGaN waveguiding layers," *Japanese Journal of Applied Physics*, Vol. 46, No. 9L, L820, 2007.
10. Lee, S.-N., et al., "Growth and characterization of the AlInGaN quaternary protective layer to suppress the thermal damage of InGaN multiple quantum wells," *Journal of Crystal Growth*, Vol. 310, No. 16, 3881–3883, 2008.
11. Bergmann, M. J. and H. C. Casey, "Optical-field calculations for lossy multiple-layer $Al_xGa_{1-x}N/In_xGa_{1-x}N$ laser diodes," *Journal of Applied Physics*, Vol. 84, No. 3, 1196–1203, 1998.
12. Lin, Y.-D., et al., "m-plane pure blue laser diodes with p-GaN/n-AlGaN-based asymmetric cladding and InGaN-based wave-guiding layers," *Applied Physics Letters*, Vol. 95, No. 8, 081110–081110, 2009.
13. Koch, T. L. and U. Koren, "Semiconductor lasers for coherent optical fiber communications," *Journal of Lightwave Technology*, Vol. 8, No. 3, 274–293, 1990.