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ABSTRACT

We present high-power GaN-based blue superluminescent diodes (SLDs) with bend waveguides. The devices were grown on a c-plane GaN free-standing substrate by metal–organic chemical vapor deposition. Studies on waveguide design were conducted to increase the output power of SLDs. Low spectral modulation had been obtained by optimizing the bend angle of the ridge waveguide. An output power as high as 510 mW had been obtained for SLDs emitting at 441 nm with a full width at half maximum of 4.4 nm.

Superluminescent diodes (SLDs) is a kind of semiconductor emitter based on spontaneous emission amplification, which combines the feature of high power density of laser diodes (LDs) and wide spectrum of light-emitting diodes (LEDs). An SLD has a short coherence length and wide emission spectrum, making it an ideal light source for pico-projectors and optical coherence tomography (OCT). GaN-based SLDs can achieve subcellular axial and lateral resolution as the light source of OCT due to its short emission wavelength. SLDs have also been proven to be a promising light source with dual functions of spot-free white light illumination and Gbps data communication. The first nitride SLD with a tilted facet was reported by Feltin et al. in 2009. From then on, GaN-based SLDs have continued to develop toward longer emission wavelengths, higher output power, and wider emission spectra.

Bend waveguides are often used in SLDs to increase the mirror loss to suppress lasing. An et al. revealed the influence of waveguide parameters on the performance of Gas SLDs through simulation. They found that the width of a ridge waveguide greatly affected the bend loss in the case of shallow etching of the ridge bend waveguide. They also found that a small radius of curvature of the bend waveguide increased the bend loss. Therefore, these waveguide parameters will have a great impact on the output power of SLDs. However, there are few experiments to study the influence of these parameters on the performance of GaN-based SLDs.

In this work, GaN-based blue SLDs with an ITO upper cladding layer had been designed and fabricated. The waveguide length, ridge width, and bend angle of SLDs had been studied in detail both by simulations and experiments. An output power as high as 510 mW at 441 nm under a pulse current of 1 A had been achieved while the full width at half maximum of the spectrum was 4.4 nm. The high-resolution spectra measurement confirmed low spectral modulation of the SLD.

A blue SLD epitaxial structure was grown on a c-plane free-standing GaN substrate by metal–organic chemical vapor deposition (MOCVD) equipment. As shown in Fig. 1(a), the epitaxial structure consisted of a silicon (Si)-doped n-Al0.08Ga0.92N cladding layer, a Si-doped n-GaN layer, a Si-doped n-In0.16Ga0.84N multiple quantum well (MQW), an unintentional-doped In0.02Ga0.98N waveguide layer, a two-period unintentional-doped In0.16Ga0.84N/GaN multiple quantum well (MQW), an unintentional-doped In0.02Ga0.98N waveguide layer, a magnesium (Mg)-doped p-Al0.20Ga0.80N electron blocking layer, a p-AlGaN/p-GaN superlattice structure as the p-cladding...
layer, a heavily doped contact layer, and an ITO acting as both the upper cladding layer and the p-electrode.

In order to suppress lasing, it is necessary to increase the mirror loss \( \alpha_m \), which can be expressed as

\[
\alpha_m = \frac{1}{2L} \cdot \ln\left[1/(R_1 \cdot R_2)\right],
\]

where \( L \) is the cavity length, \( R_1 \) is the front facet reflectivity, and \( R_2 \) is the rear facet reflectivity. According to Eq. (1), the mirror loss can be increased by reducing the facet reflectivity. Typically, the facet reflectivity needed to be lower than \( 10^{-2} \). There are many different methods to reduce reflectivity such as fabricating bent, curved, or tilted waveguide geometries and depositing anti-reflection coating.

We fabricated a 1/4 wavelength anti-reflectivity coating with 1%/99% coating 1%/99% for wavelengths from 430 to 450 nm. In order to decrease facet reflectivity further, the ridge waveguide was tilted a few degrees. When the wavefield \( F \) is incident on the facet obliquely, a part of the reflected wavefield \( F^r \) will be coupled back to the waveguide and excite the guided mode \( F_e \). The modal reflectivity \( R_1 \) is given by the following formula:

\[
R_1 = R_0 \cdot \frac{\int_{-\infty}^{\infty} F_r^* F_e dx' \int_{-\infty}^{\infty} |F_e|^2 dx'}{\int_{-\infty}^{\infty} |F_r|^2 dx' \int_{-\infty}^{\infty} |F_e|^2 dx'},
\]

where \( R_0 \) is the reflectivity of air and the cavity facet. We use the transfer matrix method to calculate the effective refractive index difference inside and outside the ridge. Figure 1(b) shows modal reflectivity \( R \) for SLDs with 2, 3, and 4 \( \mu m \) ridge width as function of the bend angle for a refractive index difference \( \Delta n \). Since GaN-based SLDs are broad-spectrum light sources with an FWHM of about 3–10 nm, we calculated the average modal reflectance of ridge for SLDs with 2, 3, and 4 \( \mu m \) for wavelengths from 435 to 445 nm. As shown in Fig. 1(b), the modal reflectivity decreases with the increase in the tilt angle, and the minimum value appears at some specific angles.

In order to experimentally investigate the influence of the bend angle of the waveguide on the output power of the SLDs, SLDs with different angles of bend waveguides for two different waveguide lengths were fabricated (A1–A5 and A6–A8). The details of the device parameters are shown in Table I. Bend angles of 4.75°, 5°, 6.2°, and 7° correspond to the minimum value of modal reflectivity, as shown in Fig. 1(b), while a bend angle of 3.6° is chosen as a comparison. In Fig. 2, the light–current (L–I) characteristics of the device were measured up to 1 A under pulse conditions; the pulse width is 0.4 \( \mu s \), and the repetition rate is 10 kHz. In Fig. 2(a), device A1 has the highest output power. However, through the analysis of the emission spectrum with a wavelength resolution of 0.1 nm, as shown in Fig. 2(c), the FWHM of the emission spectrum of device A1 drops below 2 nm under an injection current of 800 mA, which indicates that the device has lased under this operation current. This indicates that a reflectivity of \( 10^{-5} \) is not sufficient to suppress lasing. Among devices A2–A5, which have larger mirror loss, the output power becomes smaller under the same current as the bend angles increase. This is attributed to the fact that as the radius of curvature decreases, the bend loss of the waveguide increases, resulting in smaller output power. The maximum power of 510 mW is obtained at a bend angle of 4.75° under 1 A injection current, and the slope efficiency is about 0.9 W/A, both of which are comparable to literature reports. The FWHM under 1 A injection current is 4.4 nm, indicating that it works as an SLD. Among devices A6–A8, it can be seen from Fig. 2(b) that larger output power is obtained at a bend angle of 5° and 6.2° under the same current. However, as shown in Fig. 2(d), the FWHMs of the emission spectra indicate that device A6 has lased under an injection current of 500 mA and device A7 has

![FIG. 1. (a) Schematic structure of blue SLDs. (b) Average modal reflectivity dependence on tilted angles for various ridge widths.](image-url)
FIG. 2. (a) Comparison of power between SLDs with different bend angles. The ridge waveguide is composed of a 600 μm straight waveguide and a 600 μm bend waveguide. (b) Comparison of power between devices with different bend angles. The ridge waveguide is composed of an 800 μm straight waveguide and a 400 μm bend waveguide. (c) FWHM of devices A1, A2, A3, A4, and A5. (d) FWHM of devices A6, A7, and A8.

Lased under an injection current of 800 mA. For devices with a longer straight waveguide, larger optical gain is obtained so that larger mirror loss and bend loss are needed to suppress lasing. Device A8 has larger bend loss than devices A6 and A7; therefore the SLD with a large output power of 500 mW is obtained at a bend angle of 7° under 1 A injection current.

Figure 3 show the optical power vs current density (L–J) characteristics of SLDs with different ridge widths (B1–B3). The details of device parameters are shown in Table II. It should be noted that due to the optical gain saturation, the optical power dependence on the current density changes from exponential increase to linear increase. It can be seen that the devices with narrower ridges have a higher rising current density, which is similar to the threshold current density

TABLE II. The structural parameters of different ridge widths and different waveguide length SLDs.

| Group 2 | B1–3 |
|---------|------|
| Coating | 1%/99% |
| Cavity length | 1200 μm |
| Straight waveguide | 600 μm |
| Bend waveguide | 600 μm |
| Ridge width | 2, 3, 4 μm |
| Bend angle | 4.75° |
FIG. 4. (a) and (b) The high-resolution spectra of the SLDs with a bend angle of 4.75° and 5° under different injection currents. (c) For the SLDs with a ridge width of 3 μm and a bend angle of 4.75° and 5°, the spectral modulation depth changes under different currents.

Spectral modulation is another important parameter for SLDs, especially when it is applied in high-resolution OCT. For a laser, this means that the devices with a narrower ridge begin to amplify spontaneous emission under higher current densities. There are two main reasons for the increase in the rising current density. First, injection efficiency decreases for devices with narrower ridges due to the current spreading effect. Second, the scattering optical loss caused by the roughness of ridge sidewalls increases for devices with narrower ridges. Therefore, SLDs with wider ridge widths can start superluminescence mode under lower current density.

Spectrum modulation can be defined by the following formula:

$$\sqrt{R_1 \cdot R_2} \approx \frac{m_s}{2G_s} \quad G_s \gg 1,$$

where $G_s$ is the single-pass optical gain. It can be seen from formula (3) that a small reflectivity requires at least one facet to achieve low $m_s$. A series of SLDs with different bend angles were packaged. The cavity length of 1200 μm was composed of a 600 μm straight waveguide and a 600 μm bend waveguide. The ridge width is 3 μm, and the bend angles are 4.75° and 5°, respectively. Then electroluminescence (EL) spectra under both pulse operation and continuous wave (CW) operation were measured by a high-resolution spectrometer with a wavelength resolution of 0.006 nm. However, the change in modulation depth under the two conditions is very small, and we will show the modulation spectrum under CW operation in the following discussion. The modulation depth can be calculated as the difference between the maximum value of the entire spectrum and the maximum value of the unmodulated part of the spectrum. The high-resolution spectra of the SLD with a bend angle of 4.75° and 5° at different currents under CW operation are shown in Figs. 4(a) and 4(b). It can be seen that the blueshift of the peak wavelength is caused by the built-in polarization electric field and the redshift is caused by the thermal effect of the device under high injection current. The modulation depth of the device with a bend angle of 4.75° and 5° at different currents is shown in Fig. 4(c). For the device with a bend angle of 4.75°, the modulation depth increases slowly with the increase in current. The modulation depth is 0.07 at a current of 800 mA, indicating low modulation characteristics under large injection current. For the device with a bend angle of 5°, the modulation depth increases more quickly with the current. The modulation depth is 0.06 under 500 mA operation current, which is relatively high spectral modulation. This result proves the dependence of facet reflectivity on the bend angle. In the previous calculation, when the ridge width was 3 μm, compared with the devices with a bend angle of 5°, the devices with a bend angle of 4.75° had a smaller facet reflectivity.

In summary, we demonstrated the influence of waveguide design on the output power and spectral modulation of blue SLDs. The effect of bend loss on SLD output power was verified through experiments. We found that SLDs with longer straight waveguides obtain the maximum output power at larger bend angles. In addition, the SLDs with wider ridge widths can start superluminescence mode under lower current density. We compared the effects of bend angles on spectral modulation and obtained a very low spectral modulation for SLDs with a bend angle of 4.75°. Finally, we realized a GaN-based SLD emitting at 441 nm with a slope efficiency of 0.9 W/A, resulting in an optical power larger than 500 mW at 1 A under pulse conditions.

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DATA AVAILABILITY
The data that support the findings of this study are available within the article.

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