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DBR-induced modification of turn-on delay and photon response time of ZnO nanowire lasers

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A ZnO nanowire laser (NWL) with an emission wavelength of approximately 385 nm, incorporating 0–12 pairs of distributed Bragg reflectors (DBRs), has been proposed and investigated by numerical simulation. The well-known double rate equations of the laser diode (LD) were solved numerically using the fourth-order Runge–Kutta method to analyze relaxation oscillation (RO) and photon transient response. The simulation results reveal that RO amplitude increases with increasing the number of DBR pairs, whereas the RO frequency decreases. Furthermore, the numerical results demonstrate that the turn-on delay time is significantly reduced as the DBR pair number increases, owing to the higher photon cavity lifetime.

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Keywords: ZnO nanowire laser, Relaxation oscillation, Turn-on delay time, Optical communication systems

1. Introduction

ZnO is an essential material and a dynamic research topic in modern technology, particularly for high-performance LEDs, ultraviolet (UV)-sensitive photodetectors, and laser diodes (LDs) employed in optical communication systems. Furthermore, semiconductor ZnO nanowire lasers (NWLs) are highly suitable for applications in nanophotonic circuits, chemical and biological sensing, medical imaging, and drug delivery systems [1,2].

Since the threshold operating current of an LD is a critical parameter that must be minimized to enhance output power, efforts have focused on improving NWLs by integrating distributed Bragg reflectors (DBRs) at their base, as reported by several research groups [3-6]. Moreover, the incorporation of DBRs into NWLs may also affect other characteristics of the LD [7].

It is necessary to consider the balance between different characteristics and requirements. In addition, modification of photon cavity lifetime (τ_p) is expected with assisted DBRs.

On the other hand, due to its wide bandgap (3.37 eV), high electron mobility, and large exciton binding energy (≈60 meV), ZnO has been recognized as a leading semiconductor material and extensively investigated [8, 9]. Owing to these distinctive properties, ZnO NWLs are expected to demonstrate unique turn-on delay times and photon transient responses, particularly when DBRs are incorporated at the ends of the nanowires (NW) that serving as an active optical medium.

The present numerical simulation study employs the standard double rate equations of laser diodes to examine how the number of distributed Bragg reflector pairs influences the photon time response, relaxation oscillation frequency, and turn-on delay time in ZnO nanowire laser structures with and without DBRs.

2. ZnO nanowire laser structure and parameters

In the proposed ZnO NWL structure, the DBR is assumed to consist of 2–12 periods of alternating SiO_2/SiN_x dielectric layers located at the bottom of the LD structure. The reflectivities at the two ends of the ZnO NWL cavity are taken as 0.04 (4%) for the sapphire/ZnO interface and 0.09 (9%) for the ZnO/ITO/glass interface, in order to replicate the real experimental structure reported in the laboratory [6,10]. A quarter-wavelength DBR, composed of SiO_2 and SiN_x layers, is designed using the following equation [3]:

$$n_H l_H = n_L l_L = \lambda/4 \tag{1}$$

Here, n_H=2 is the refractive index of SiN_x with thickness l_H, and n_L = 1.46 is the refractive index of SiO_2 with thickness l_L. Substituting these refractive index values into Eq. (1) gives l_H = 47.5 nm and l_L = 65.07 nm. Based on this, the reflection response (R_r) of the DBR at a wavelength near 385 nm can be expressed as [3]:

$$R_r = \frac{1-\left(\frac{n_H}{n_L}\right)^{2N}\frac{n_H{}^2}{n_a n_b}}{1+\left(\frac{n_H}{n_L}\right)^{2N}\frac{n_H{}^2}{n_a n_b}} \tag{2}$$

Here, n_a=1 is the refractive index of air, n_b=3.5 is the refractive index of the Si substrate, and N is the number of bilayers in the DBR. The reflectivity of the DBR can then be calculated as $R_f = |R_r|^2$ [6].

Assuming a NW gain medium diameter of 100 nm in the designed ZnO NWL structure yields single-mode laser emission, with an optical confinement factor of approximately 0.3, calculated using the following formula [11,12]:

$$\Gamma = \sigma / A_{\mathrm{eff}} \tag{3}$$

$$A_{\mathrm{eff}} = (\lambda / n_{\mathrm{eff}})^2,$$

where, σ denotes the cross-sectional area of the NW, A_{eff} is the effective mode area, and n_{eff} is the effective refractive index of the NW material (ZnO).

This approximation formula is applicable when the nanostructures are uniform, as assumed in the present study, leading to a uniform field intensity across the nanowires.

The photon cavity lifetime (τ_p) for the ZnO NWL can be expressed as:

$$\frac{1}{\tau_p} = \frac{c}{n}(\alpha_i + \alpha_m)$$

$$\frac{1}{\tau_p} = \frac{c}{n}\left(\alpha_i + \frac{1}{2L} ln \frac{1}{R_1 R_2}\right), \tag{4}$$

where α_i and α_m are internal and mirror losses, respectively.

Since $\alpha_m \gg \alpha_i$ in ZnO NWLs, α_i can be neglected, and τ_p is therefore primarily determined by α_m. For a ZnO NWL without a DBR, τ_p is calculated to be 11.85 fs. This extremely low value arises from the low facet reflectivities of the ZnO nanowires. Consequently, incorporating a DBR into the ZnO NWL design is expected to increase the τ_p value significantly.

Table 1 summarizes all the parameters required for the numerical simulation study, while Fig. 1 illustrates the proposed ZnO NWL design structures, both with and without DBRs.

Table 1. Numerical simulation parameters for DBR-assisted ZnO NWL

Parameter	Symbol	Value
Wavelength	λ	385 nm
Cavity length	L	4 μm
Nanowire diameter	D	100 nm
Carrier density at threshold	N_{th}	1.1×10^{18} cm^{-3} [10]
Active region volume	V_a	5×10^{-11} cm^3
Front facet reflectivity	R_1	9% [10]
Rear facet reflectivity	R_2	4% [10]
Carrier number at transparency	N_o	1×10^8
Carrier lifetime	τ_n	0.3 ns [13]
Photon cavity lifetime (without DBR)	τ_p	11.85 fs
Differential gain	g_o	5×10^{-16} cm^2 [14]
Spontaneous emission factor	β	10^{-3}
Optical confinement factor	Γ	≈ 0.3
ZnO refractive index	n_z	2.5
Mirror loss (without DBR)	α_m	7×10^3 cm^{-1}

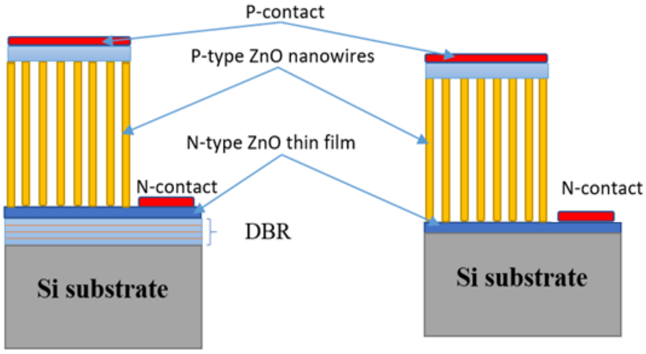

Fig. 1. The proposed ZnO design structures with DBR (left) and without DBR (right) (colour online)

3. Steady-state solution

The dynamic response of the LD, including the ZnO NWL under investigation, can be analyzed using the well-known double rate equations [15]:

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_s} - g_o(N - N_o)S \tag{5}$$

$$\frac{dS}{dt} = \Gamma\beta\frac{N}{\tau_s} + \Gamma g_o(N - N_o)S - \frac{S}{\tau_p}, \tag{6}$$

where I is the bias current, q is the elementary charge, Γ is the optical confinement factor, N_o is the carrier number at transparency, and τ_n and τ_p are the carrier and photon lifetimes, respectively. Additionally, β is the spontaneous emission factor, and g_o is the differential gain (in s^{-1}).

The relaxation oscillation (RO) frequency (f_r) is an important parameter to characterize and can be determined by applying a standard small-signal analysis to the above rate equations [16]:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{\Gamma g_o S_o}{\tau_p}}, \tag{7}$$

where S_o denotes the photon number under steady-state conditions.

The turn-on delay time (t_d) of an LD, based on the double rate equations, is given by [17]:

$$t_d = \tau_n ln \frac{I}{I - I_{th}}, \tag{8}$$

where I_{th} denotes the threshold operating current of the LD.

4. Results and discussion

A critical parameter for the designed ZnO NWL, with or without DBRs, is the photon cavity lifetime (τ_p), which is strongly affected by the number of DBR pairs that enhance reflectivity at the NWL end. Figs. 2 and 3 illustrate these relationships: Fig. 2 shows the reflectivity of the bottom LD cavity with the integrated DBR as a function of the number of DBR pairs, while Fig. 3 presents the photon lifetime versus DBR pair number.

It is noticeable in Fig. 2 that the reflectivity of the end ZnO nanowire reaches saturation at 11 DBR pairs. Therefore, for an effective mirror of the gain medium, using 12 DBR pairs as a maximum number is sufficient to achieve high reflectivity without complicating the ZnO NWL structure, and adding more than 12 pairs offers no significant benefit.

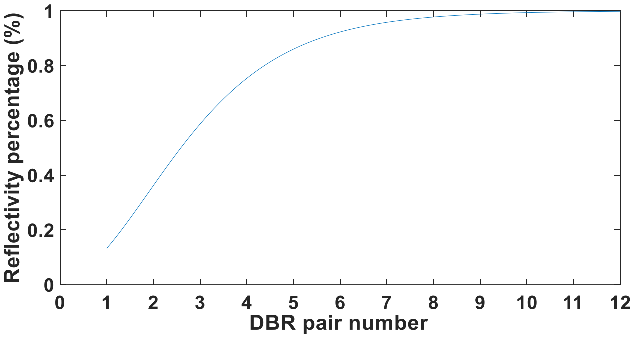

Fig. 2. Reflectivity percentage as a function of the number of DBR pairs

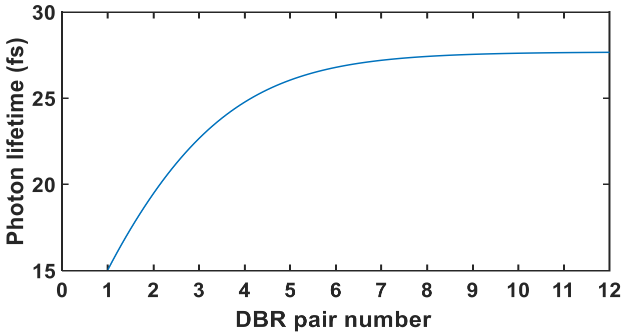

Fig. 3. Photon lifetime as a function of the number of DBR pairs

It is noteworthy that τ_p is extremely low, on the order of femtoseconds, due to the low reflectivities of the front and back mirrors. In contrast, τ_p can be increased by adding more DBR pairs at the nanowire base, which serve as the rear mirror for the ZnO NWL gain medium.

The threshold current (I_{th}) of an LD directly influences its transient characteristics, including relaxation oscillation, turn-on delay time, and photon transient response. Integrating DBRs into the LD cavity, particularly at the bottom, enhances reflectivity and optical feedback within the ZnO NWL cavity, thereby increasing τ_p. Consequently, the threshold gain required for lasing is reduced, leading to a lower threshold current, as illustrated in Fig. 4.

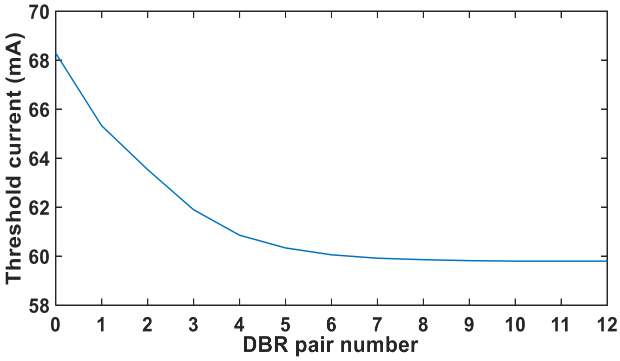

Fig. 4. Dependence of the ZnO NWL threshold current on the number of DBR pairs

Fig. 5 illustrates the transient response of the photon number for ZnO NWLs without DBRs and with 12 DBR pairs, with a bias current of 70 mA (close to the LD threshold without DBRs), switched on at 0 s. A clear delay in photon response, known as the turn-on delay time (t_d), is observed. This delay can be readily estimated using Eq. (8). The dependence of t_d on LD bias currents of 70, 72, and 74 mA as a function of the number of DBR pairs is shown in Fig. 6.

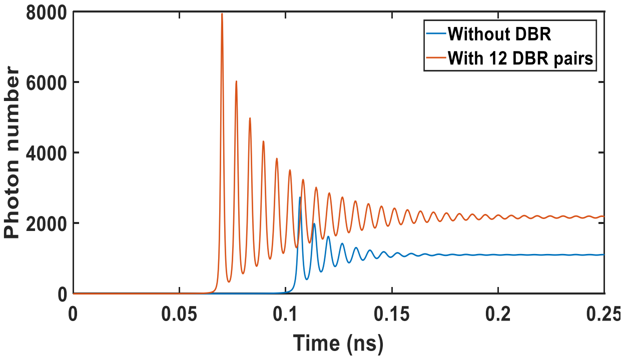

Fig. 5. Transient response of the photon number (colour online)

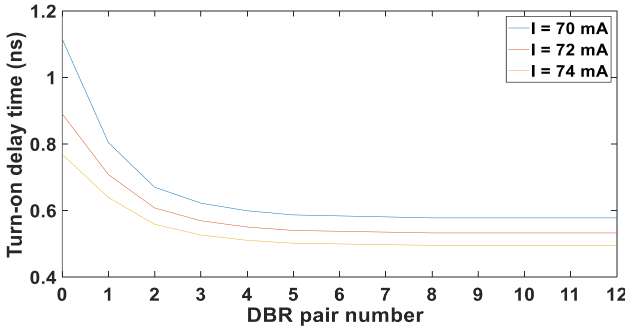

Fig. 6. Turn-on delay time at different bias current as a function of the number of DBR pairs (colour online)

Eq. (7) indicates that the RO frequency depends strongly on both the photon number and the photon lifetime. Since the photon number near the I_{th} is extremely low, its effect on RO frequency is minimal. Consequently, the dominant factor influencing the RO frequency in a ZnO NWLs is τ_p, which is enhanced by the inclusion of DBRs, as discussed earlier. As a result, the RO frequency is lower in ZnO NWLs with DBRs, as illustrated in Fig. 7.

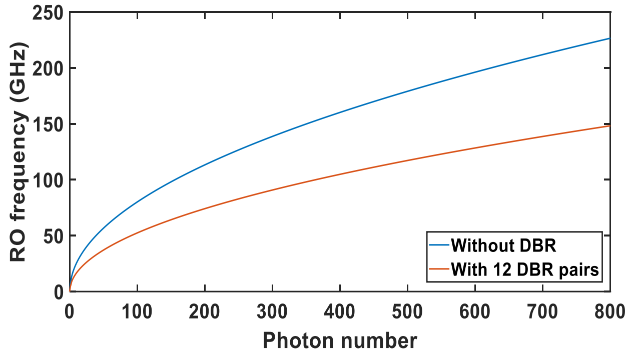

Fig. 7. Dependence of the RO frequency on the number of DBR pairs (colour online)

The RO frequencies of ZnO NWLs reach 150 GHz with DBRs and 220 GHz without DBRs. This enhancement is attributed to the high differential gain and photon number near the I_{th}, making these devices suitable for high-speed modulation. These results are consistent with related experimental studies, which reported ultrafast dynamics in ZnO NWLs, with RO frequencies on the order of 100 GHz depending on the device design and specific parameters [18].

5. Conclusion

Modeling ZnO nanowire lasers (NWLs), including distributed Bragg reflectors (DBRs) as rear mirrors, through numerical simulations is essential for optimizing device performance in advanced nanophotonic applications and optical communication systems. Key ZnO NWL properties, such as threshold current (I_{th}), photon lifetime (τ_p), photon transient response, relaxation oscillation (RO) frequency, and turn-on delay time (t_d), are strongly influenced and enhanced by the inclusion of DBRs at the base (bottom of the NWLs) of the gain medium. While the DBR reduces the threshold current operation of ZnO NWL, it increases the cavity photon lifetime, which in turn lowers the RO frequency as a function of DBR number. The DBRs consequently reduce the modulation bandwidth. Therefore, a trade-off should be considered between improved lasing characteristics of ZnO NWLs and the capability of the high-speed modulation.

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