

## Polarization characteristics of ZnO rib waveguide random lasers

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Ultraviolet ZnO rib waveguide random lasers with stripe width ranging from 1.7 to 6.5  $\mu\text{m}$  have been fabricated. It is found that the ZnO random lasers demonstrate strong TE lasing emission especially for rib waveguide with a narrower width. Rate equation analysis has shown that the dominant TE lasing emission is due to the corresponding large confinement factor and scattering strength inside the random media with rib waveguide. In addition, Fourier transform studies of the lasing spectra show that the width of rib waveguide constrains the formation of closed-loop paths of lights and, hence, reduces the number of lasing peaks. © 2006 American Institute of Physics. [DOI: 10.1063/1.2181634]

The formation of an optical waveguide is a powerful approach to confine and control the propagation of light.<sup>1</sup> This idea has been extended to enhance the lasing performance of organic<sup>2</sup> and inorganic<sup>3</sup> random media. However, if the designed polarization of the optical waveguide is different from that of the random medium, the corresponding lasing efficiency can be deteriorated. This is because since the presence of optical waveguide may alter the light scattering paths, the polarization of the lasing emission does not only depend on the size and disordering of the random medium.<sup>4,5</sup> Hence, it is necessary to study the polarization properties of random media under the influence of optical waveguide. In this letter, we investigate the polarization characteristics of ZnO rib waveguide random lasers. Rate equations analysis and Fourier transform studies were used to account for the polarization dependency random laser action under the influence of rib waveguide.

Figure 1(a) shows the schematic of the ZnO rib waveguide random laser. A  $\sim 400$  nm thick  $\text{SiO}_2$  buffer layer was first formed on (100) Si wafer by thermal dry oxidation. Then, a  $\sim 180$  nm thick ZnO film was deposited on the buffer layer by the filtered cathodic vacuum arc technique.<sup>3</sup> To form the random cavities, postgrowth annealing of the ZnO film was carried out in a furnace in open air at 900 °C for 2 h.<sup>3</sup> Subsequently, a line mask was made on the surface of the annealed ZnO film by photolithography technique. The unmasked ZnO region was then etched to the  $\text{SiO}_2$  buffer layer at an etching rate of  $\sim 4.5$  nm/min by ion-beam sputtering method.<sup>3</sup> A low ion-beam current and voltage were used to prevent hardening of the photoresist and surface damage to the unmasked region. Several ZnO rib waveguide random lasers with a fixed length ( $\sim 0.1$  cm) and width,  $w$  ( $\sim 1.7$ – $6.5$   $\mu\text{m}$ ) were fabricated.

To study the room-temperature UV lasing characteristics of the samples, unpolarized Nd-yttrium-aluminum-garnet laser (355 nm) at pulsed operation (6 ns, 10 Hz) was used to pump the samples optically via a cylindrical lens along the rib waveguide. The length and width of the pump stripe was  $\sim 0.2$  cm and  $\sim 200$   $\mu\text{m}$ , respectively. In general, all the samples exhibit a broad spontaneous emission spectrum with

emission peak at  $\sim 385$  nm under optical excitation of intensity,  $P < P_{\text{th}}$ , where  $P_{\text{th}}$  is the pump threshold. For  $P > P_{\text{th}}$ , sharp lasing peaks start to emerge and the number of lasing peaks increases with the increase of  $P$  until saturation (i.e.,  $\sim 2 \times P_{\text{th}}$ ) is reached. Figure 2(a) shows the influence of  $w$  on the TE lasing spectra of the samples at  $P = 2 \times P_{\text{th}}$ . For the annealed ZnO film (without a rib waveguide), the emergence of many lasing peaks overlapped to form a broad spectrum. For the rib waveguide laser with  $w \sim 6.5$   $\mu\text{m}$ , the corresponding emission spectrum is similar to that of the annealed film except that the overall spectrum width is reduced from  $\sim 6.4$  to  $\sim 4.1$  nm. Further reduction of  $w$  does not change the spectrum width until  $w$  reaches  $\sim 3.0$   $\mu\text{m}$ . It is observed that the number of lasing peaks is significantly reduced and can be resolved spectrally to  $\sim 13$  peaks. Figure 2(b) shows the TE spectra of sample with  $w \sim 1.7$   $\mu\text{m}$ . It is clearly observed that the emission spectrum is narrowed to  $\sim 1$  nm. In addition, the total number of lasing peaks is  $\sim 6$  at  $2 \times P_{\text{th}}$  and the linewidth of each lasing peak is  $\sim 0.4$  nm. The inset in Fig. 2(b) shows the near field profiles of the TE polarization at  $2 \times P_{\text{th}}$  for  $w$  at 6.5 and 1.7  $\mu\text{m}$ , respectively. At  $w = 6.5$   $\mu\text{m}$  (1.7  $\mu\text{m}$ ), three (one) transverse modes, which indicates strong confinement of light inside the rib waveguides, are (is) observed. Figures 2(c) and 2(d) show the corresponding TM lasing spectra of the samples. The trend of the change in the emission spectra is similar to that of TE polarization. The inset of Fig. 2(d) compares the num-

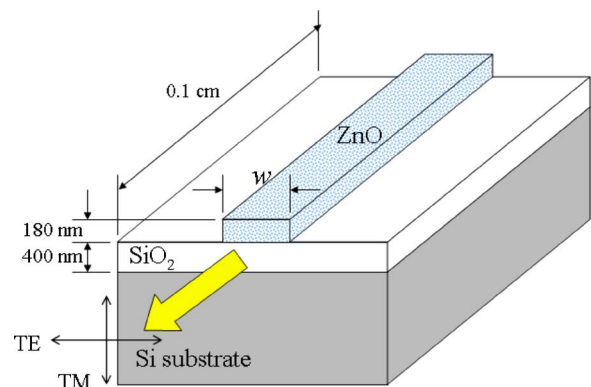


FIG. 1. Schematic of ZnO rib waveguide random laser with stripe of width  $w$ .

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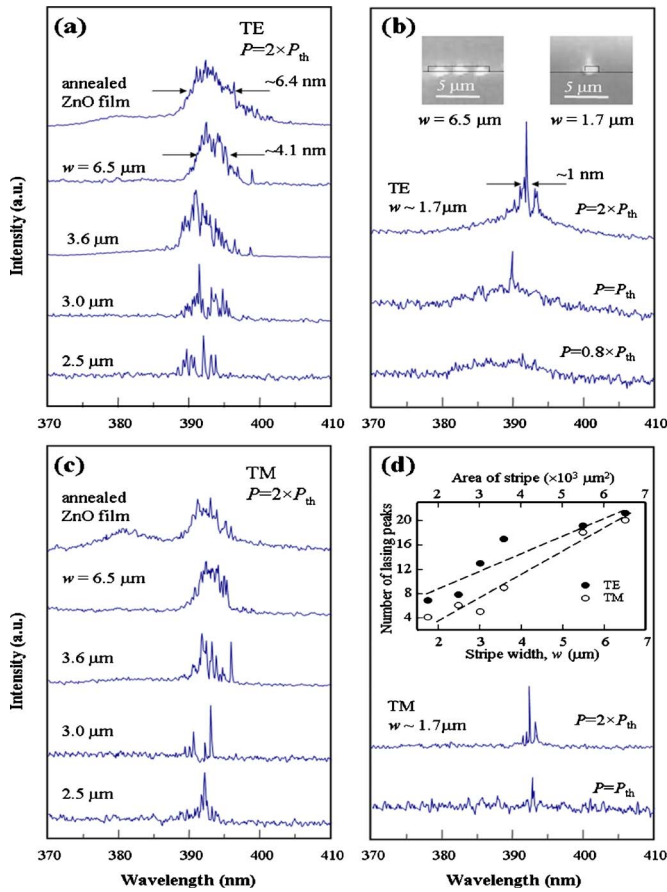


FIG. 2. (a) TE optical spectra of ZnO random lasers with various  $w$  at  $P = 2 \times P_{th}$ . (b) TE optical spectra of ZnO rib waveguide for  $w \sim 1.7 \mu\text{m}$  at various  $P$ . Inset shows the near field profiles for  $w = 6.5$  and  $1.7 \mu\text{m}$  sample at  $P = 2 \times P_{th}$ . (c) TM optical spectra of ZnO random lasers with various  $w$  at  $P = 2 \times P_{th}$ . (d) TM optical spectra of ZnO rib waveguide for  $w \sim 1.7 \mu\text{m}$  at various  $P$ . Inset plots the number of TE and TM lasing peaks against  $w$  and area of stripe. Optical spectra of annealed ZnO thin film (i.e., without rib waveguide) are also shown in the figures for comparison.

ber of lasing peaks for both TE and TM polarizations versus  $w$  at  $2 \times P_{th}$  (i.e., saturation pump intensity). It shows fewer lasing peaks for TM polarization, especially when  $w$  is small ( $< 3.6 \mu\text{m}$ ). The near field profile of TM polarization is similar to that of TE polarization (except the emission intensity is much weaker) and is not repeated here.

Figure 3 plots  $P_{th}$  for both TE and TM polarizations versus  $w$ . It is observed that  $P_{th}$  for both polarizations increases with the reduction of  $w$  and the increase of  $P_{th}$  for TM polarization is faster than that of TE polarization. The  $P_{th}$  of the annealed ZnO film for both polarizations is found to be  $\sim 0.28 \text{ MW/cm}^2$ . The variation of  $P_{th}$  for both polarizations with  $w$  can be approximated by  $P_{th,TE(TM)} \sim A_{TE(TM)} + \chi_{TE(TM)}/w$  where  $A_{TE(TM)}$  and  $\chi_{TE(TM)}$  are two constants to be determined. As  $P_{th}$  of both polarizations is roughly inversely proportional to  $w$ , the rib waveguide lasers are considered to exhibit two-dimensional (2D) random laser action.<sup>6</sup> It can be shown that  $P_{th,TM}/P_{th,TE}$  increases (i.e., from 1 to  $\sim 1.23$ ) with the decrease of  $w$ . This indicates that the cavity loss of TM polarization is always higher than that of TE polarization and thus results in higher pump threshold. Therefore, the relatively larger cavity loss of TM polarization reduces the probability of forming random cavities so that fewer lasing peaks are observed from the spectra. Fig. 3 also plots the ratio of slope efficiency between TE and

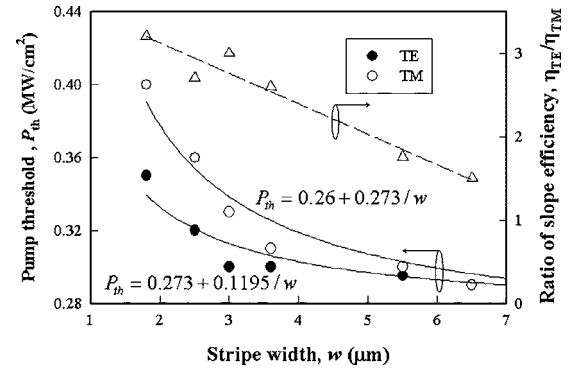


FIG. 3. The two extrapolated curves (solid lines) show the relationship between the pump threshold  $P_{th}$  and the stripe width  $w$ . It is found that  $A_{TE}$  ( $A_{TM}$ ) is  $0.273 \text{ MW/cm}^2$  ( $0.26 \text{ MW/cm}^2$ ) and  $\chi_{TE}$  ( $\chi_{TM}$ ) is  $0.1195 \text{ MW/cm}^3$  ( $0.273 \text{ MW/cm}^3$ ). The linear fit graph (dashed line) shows the ratio of slope efficiency  $\eta_{TE}/\eta_{TM}$  at different  $w$ .

TM polarizations,  $\eta_{TE}/\eta_{TM}$ , versus  $w$ .  $\eta_{TE}/\eta_{TM}$  increases (from  $\sim 1.4$  to  $\sim 3.2$ ) with the reduction of  $w$  (from  $6.5$  to  $1.7 \mu\text{m}$ ). This shows that TE polarization is dominant in rib waveguide random lasers especially with small  $w$ .

From the earlier experimental results, two phenomena, which are different from other random lasing media, are observed from our rib waveguide random lasers: (1) The rib waveguide lasers are TE dominant while others mostly, reported to be TM dominant.<sup>4,5,7</sup> (2) The number of lasing peaks from the rib waveguide lasers is less than that from the circular disk structure<sup>6</sup> (i.e., for gain area of  $\sim 2500 \mu\text{m}^2$ , the saturated number of lasing peaks from the rib waveguide is  $\sim 14$  while that from the disk structure is  $\sim 35$ ).

The polarization characteristics of rib waveguide random lasers can be understood from the rate equations for population density,  $n$  and photon number density,  $\phi$ , as shown.<sup>1</sup>

$$\frac{dn}{dt} = \frac{P}{h\nu d} - \frac{n}{\tau} - c_g \sigma n \phi, \quad (1a)$$

$$\frac{d\phi}{dt} = -\frac{\phi}{\tau_p} + c_g \Gamma \sigma n \phi, \quad (1b)$$

where  $h\nu$  is the photon energy at pump wavelength,  $d$  is the thickness of the active medium,  $\tau$  is the carrier lifetime,  $c_g$  is the group velocity,  $\sigma$  is the emission cross section,  $\Gamma$  is the confinement factor, and  $\tau_p$  is the photon escape lifetime from the random medium. From Eq. (1), the slope efficiency,  $\eta$  ( $\equiv \phi d h\nu / P$ ) of both polarizations can be expressed as  $\eta = \Gamma \tau_p (1 - h\nu d / c_g \sigma \Gamma \tau_p P)$ . For large  $P$ ,  $\eta \sim \Gamma \tau_p$  such that

$$\frac{\eta_{TE}}{\eta_{TM}} \approx \frac{\Gamma_{TE} \tau_{p,TE}}{\Gamma_{TM} \tau_{p,TM}}. \quad (2)$$

From Eq. (2), the relationship between  $\eta_{TE}/\eta_{TM}$  and  $\Gamma_{TE}/\Gamma_{TM}$  indicates that the polarization of the random media is affected by the presence of optical waveguide. From Eq. (1), we can write  $P_{th}/h\nu d = 1/c_g \tau_p \sigma \Gamma$  so that  $\tau_{p,TE}/\tau_{p,TM} \sim P_{th,TM}/P_{th,TE}$  as  $\Gamma_{TE} \sigma_{TE}/\Gamma_{TM} \sigma_{TM} \sim 1$  (i.e., from the slope of the lines in Fig. 9 of Ref. 8). Thus,  $\tau_{p,TE}/\tau_{p,TM}$  is always greater than 1 and is increased with the reduction of  $w$ . From our effective index method calculation, it is found that  $\Gamma_{TE}$  ( $\Gamma_{TM}$ ) is approximately equal to  $0.791$  ( $0.538$ ) for rib waveguide with  $w = 6.5 \mu\text{m}$  and is reduced to  $0.764$  ( $0.492$ ) for  $w = 1.7 \mu\text{m}$ . Although the value of  $\Gamma_{TE}/\Gamma_{TM}$  is almost independent of  $w$ , it is noted that  $\Gamma_{TE} > \Gamma_{TM}$  for all  $w$ .

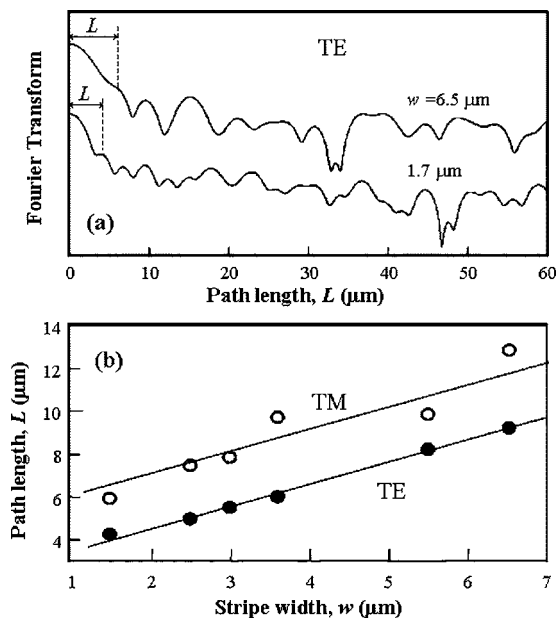


FIG. 4. (a) Fourier transform of the TE lasing spectra of ZnO waveguide random lasers with  $w=6.5$  and  $1.7 \mu\text{m}$ . (b) The variation of path length,  $L$ , (i.e., obtained from the fundamental harmonic of the Fourier transformed spectra) for both TE and TM polarizations vs  $w$ .

Hence, we can conclude that TE polarization is dominant inside the rib waveguide.

If a Fabry-Pérot cavity is used to model the rib waveguide random lasers, the equivalent effective reflectivity,  $R$ , (i.e., proportional to the scattering strength) can be associated with  $\tau_p$  by  $\tau_p^{-1} \sim c_g L^{-1} \ln(1/R)$ , where  $L$  is the path length of closed-loop paths inside the rib waveguide random laser.<sup>1</sup> Hence, the effective reflectivity for both polarizations can be related by

$$\frac{\tau_{p,\text{TE}}}{\tau_{p,\text{TM}}} = \frac{L_{\text{TE}} \ln(1/R_{\text{TM}})}{L_{\text{TM}} \ln(1/R_{\text{TE}})} > 1. \quad (3)$$

$L$  can be deduced from the fundamental harmonic of the Fourier transform of the corresponding lasing spectra.<sup>9</sup> Fig. 4(a) shows the Fourier transform of the TE spectra for  $w=6.5$  and  $1.7 \mu\text{m}$  at  $P=2 \times P_{\text{th}}$ . The relationship between  $L$  and  $w$  for both polarizations at  $P=2 \times P_{\text{th}}$  is plotted in Fig. 4(b). It is observed that  $L$  increases linearly with  $w$ . This implies that the width of the rib waveguide (with fixed length

of  $\sim 0.1$  cm) limits the light scattering closed-loop paths. This explains why the rib waveguide structure shows less lasing peaks than the disk structure for the same gain area. On the other hand, the value of  $L_{\text{TE}}/L_{\text{TM}}$  is independent of  $w$  as shown in Fig. 4(b). From Fig. 3, it is noted that the value of  $\eta_{\text{TE}}/\eta_{\text{TM}}$  [and, hence,  $\tau_{p,\text{TE}}/\tau_{p,\text{TM}}$  as given by, Eq. (2)] increases with the reduction of  $w$ . Therefore from Eq. (3), it can be shown that the reduction of  $w$  increases the value of  $R_{\text{TE}}/R_{\text{TM}}$  (since  $L_{\text{TE}}/L_{\text{TM}} < 1$  for this range of  $w$ ). As  $0 < R_{\text{TM}} < R_{\text{TE}} \leq 1$ , TE polarization experiences stronger optical feedback (i.e., large scattering strength) within the closed-loop paths than TM polarization. Therefore, the higher scattering strength of TE polarization inside the random media especially for small  $w$  also contributes to the dominant TE lasing emission. The weak optical feedback (i.e., weak scattering strength) of TM polarization may be due to the short column length of ZnO grains whereas the dominant TM polarization reported in Refs. 4, 5, and 7 is due to the infinite height (i.e., vertical direction) of the random media.

In conclusion, the polarization characteristics of ZnO rib waveguide random lasers were investigated. It is shown that ZnO rib waveguide random lasers with narrow stripe exhibit stronger TE lasing emission than the one without waveguide. Rate equation analysis has shown that the dominant TE polarization is attributed to the large  $\Gamma_{\text{TE}}$  and  $R_{\text{TE}}$  inside the random media due to the presence of rib waveguides. In addition, Fourier transform studies have shown that the width of the rib waveguide confines the closed-loop paths to a smaller region and thus reduces the number of lasing peaks.

<sup>1</sup>K. Petermann, *Laser Diode Modulation and Noise* (Kluwer Academic, Netherlands, 1988), Chap. 2.

<sup>2</sup>S. V. Frolov, Z. V. Vardeny, K. Yoshino, A. Zakhidov, and R. H. Baughman, *Phys. Rev. B* **59**, 5284 (1999).

<sup>3</sup>C. Yuen, S. F. Yu, E. S. P. Leong, H. Y. Yang, S. P. Lau, N. S. Chen, and H. H. Hng, *Appl. Phys. Lett.* **86**, 031112 (2005).

<sup>4</sup>X. H. Wu, A. Yamilov, H. Noh, H. Cao, E. W. Seelig, and R. P. H. Chang, *J. Opt. Soc. Am. B* **21**, 159 (2004).

<sup>5</sup>I. Freund, *Waves Random Media* **1**, 245 (1991).

<sup>6</sup>Y. Ling, H. Cao, A. L. Burin, M. A. Ratner, X. Liu, and R. P. H. Chang, *Phys. Rev. A* **64**, 063808 (2001).

<sup>7</sup>T. Ito and M. Tomita, *Phys. Rev. B* **66**, 027601 (2002).

<sup>8</sup>S. F. Yu, C. Yuen, S. P. Lau, and W. J. Fan, *IEEE J. Quantum Electron.* **40**, 406 (2004).

<sup>9</sup>R. C. Polson and Z. V. Vardeny, *Phys. Rev. B* **71**, 045205 (2005).