

# Enhancement of Light Emission Using ZnO Grating Nanowires: An Experimental and Numerical Study

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## Abstract

White Light Emitting Diodes (WLEDs) with improved light emission in the red region are highly desired for many applications especially for obtaining warm illumination rather than the conventional cold blue LEDs. In this work, we provide an experimental and theoretical study for a grating structure composed of ZnO nanowires (NWs) that proves to boost and directionally extract the visible and red light emission. The experimental results are compared with a theoretical and numerical model to understand this unique optical behavior.

## 1. Introduction

In recent years many research studies aimed to develop functional material structures to enhance light extraction in WLEDs. One way to accomplish this consists in structuring the most-common used phosphor in commercial white LEDs:  $Y_3Al_5O_{12}:Ce^{3+}$  (or YAG:Ce) which emits mostly between 470 and 630nm under blue radiation[1]. Recently a study showed that light extraction from YAG:Ce can be improved using plasmonic nanocubes [2]. However, the combination of yellow to green photoluminescence of the phosphor with the blue light provides a white light with poor photometric parameters, in particular a low color rendering index (CRI). This is explained by the lack of red contribution in the emission spectrum of this association: blue LED and yellow phosphor. In the framework of the SMARTLEDs project, we propose an original approach that uses ZnO grating nanowires to add red light emission. The experimental measurement of the photoluminescence (PL) demonstrates that the micro structuring of the ZnO nanowire directionally extracts and enhances the ZnO light emission. Our theoretical and electromagnetic simulations show that trapped modes within the ZnO grating NWs are responsible for these behaviors.

## 2. Structure and design

The structure proposed is represented in Fig. 1. It consists of ZnO nanowires grown in a grating manner on a quartz

substrate (Fig. 1(a)). The grating period is  $D=4\mu\text{m}$ , the width of the ZnO NWs gratings is  $w_{\text{ZnO}}=2\mu\text{m}$ , and its height is  $h_{\text{ZnO}}=0.6\mu\text{m}$ . The fabrication process is done by hydrothermal synthesis at ambient pressure according to Ref. [3-4]. The selective growth of NWs leading to grating ZnO NWs has been performed on a previously photo-patterned sol-gel derived ZnO-based resist. Fig. 1(b), shows the SEM images of the ZnO NWs, from the top while Fig.1(c) represents a cross section view.

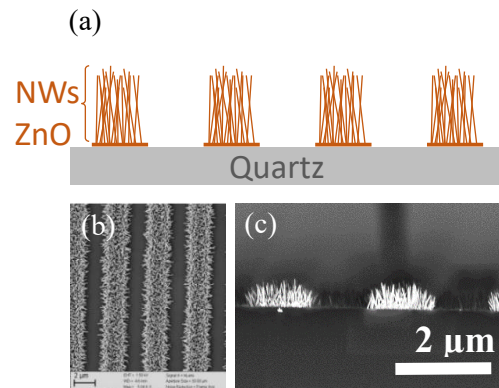


Figure 1: (a) Schematic representation of the grating ZnO NWs on a quartz substrate. (b-c) top and cross-sectional SEM images.

## 3. Experimental results

The room-temperature PL spectra of the structure are measured at several emitted angles when the grating structure is illuminated in normal incidence by blue radiation. Figure 2(a) shows the PL normalized vs the PL obtained at  $0^\circ$  as a function of the wavelength for three different angles  $50^\circ$ ,  $60^\circ$ , and  $75^\circ$ . It can be observed that the PL is doubled at  $60^\circ$  near 650 nm (Fig.2 (a)). This shows that the light extraction is increased under oblique illumination compared to that at normal incidence. This is due to a resonant mode trapped inside the ZnO gratings at a certain angle, this aspect will be discussed in the last section. The comparison of the PL measured over the range 400-800 nm as a function of the extraction angle for the grating

structure and for an unpatterned ZnO coating demonstrates that the emission is clearly boosted around  $65^\circ$  (Fig.2 (b)). The periodic micro structuring of the ZnO NWs increases by 20% the total PL integrated between  $0^\circ$  and  $90^\circ$ . These results demonstrate that higher PL is achieved with twice less active material compared to an unpatterned coating.

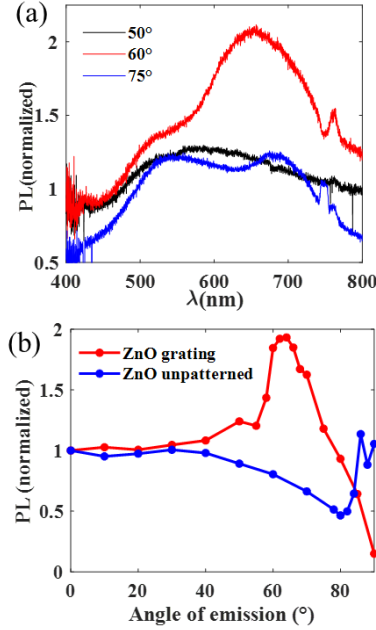


Figure 2: (a) Measured photoluminescence (normalized) under different angles of illumination ( $50^\circ, 60^\circ, 75^\circ$ ). (b) Average PL over the range 400-800nm for a ZnO grating and a coating of unpatterned ZnO on a quartz substrate.

#### 4. Electromagnetic simulations

In this part we explain the origin of this enhanced light extraction in the grating structure. For this purpose, an effective model is adopted to substitute the spiky arrangement of the ZnO NWs by a homogeneous layer of effective index and width ( $n_{\text{eff}}=1.65$ ,  $w_{\text{eff}}=1.6\mu\text{m}$ ) (Fig. 3(a)). We found that this structure supports a resonant mode trapped within the effective ZnO ribbon (Fig 3(b)). The dispersion curve is calculated by following the eigen mode using Comsol Multiphysics (inset of Fig. 3(b)). This mode originates from the guided mode within the ZnO coating that resonates in the ribbon. Qualitatively, the angular dependence agrees with Bragg-scattering theory. The angle of emission is related to the wave vector of the guided mode,  $k_g$ , and the Bragg vector of the grating,  $G = 2\pi/D$ , by  $k_0 \sin \theta = k_g + nG$ . Finally, the experimental data (red dots) extracted from the PL measurements match with the numerical model (blue dots), which proves that the enhancement of the PL is attributed to the resonant trapped mode.

#### 5. Conclusion

As a conclusion, we have shown that the grating ZnO nanowires proves to enhance light extraction up to two times

more compared with an unpatterned layer of ZnO. This improved performance obtained with twice less active material is due to the localization of the resonant mode within the ZnO ribbon. We think that resonant ZnO gratings have a high potential for many applicative developments ranging from sensors to LEDs.

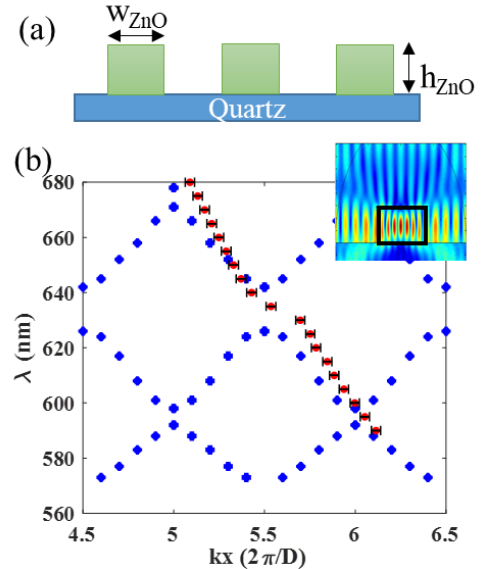


Figure 3: (a) Effective model of the ZnO grating NWs on a quartz substrate. (b) Dispersion curve of the mode resonating (inset) in the ZnO grating (blue dots). The red dots are the experimental data obtained from the measurement.

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