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Electrical control of the distributed feedback organic semiconductor laser based on holographic polymer dispersed liquid crystal grating

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ABSTRACT

In this paper, we demonstrate the electrical control of the distributed feedback (DFB) organic semiconductor laser based on a holographic polymer dispersed liquid crystal (HPDLC) grating for the first time. The grating is fabricated on the top of the organic semiconductor film to act as an external feedback structure. Experimental results show that the lasing intensity can be decreased by increasing the external electric field, and the lasing wavelength exhibits a slight blue-shift of 1.4 nm during the modulation process, indicating a good stability. The modulated performances are attributed to the decreases in the refractive index modulation and average refractive index of the HPDLC grating respectively as a result of the field-induced liquid crystal reorientation. This study provides some new ideas for the improvement of DFB organic semiconductor laser to enable envisioned applications in laser displays and integrated photonic circuits.

1. Introduction

During the past decade, electrically controllable lasers have attracted a great deal of interest as the active laser sources for various applications including wavelength division multiplexing (WDM) [1], laser displays and integrated photonic circuits [2,3], because their lasing characteristics (e.g., lasing wavelength or energy) can be easily modulated by electric field. To achieve an electrically controllable laser, a promising and efficient way is to incorporate liquid crystal (LC) in the laser resonator cavity because the orientation of LC molecules with large anisotropy and their refractive indices can be modified by external electric field. Two kinds of LCs have been widely used in the electrically controllable lasers. One is the nematic LC which is often added in optical waveguide [4–7]. The field-induced LC rotation can easily change the waveguide properties, and thus the lasing characteristics. The other one is the cholesteric LC which can form a self-assembled helical structure and result in a photonic band gap [8]. The helical structure can be deformed by LC rotation, which leads to a modulation of lasing wavelength [9] or energy [10]. Among the LC-based controllable lasers, the active laser media are always chosen to be the laser dyes since they can easily blend with LC. However, the concentration quenching effect of dyes in the pure solid film severely limits their lasing efficiencies and thus the practical application [11]. Compared to the dyes, organic semiconductor materials, as the new generation of laser media, show three advantages [12,13] of a) stronger pump absorption and gain in the solid state, b) simpler processing to make thin film for laser structure and c) capability of charge transport which opens up the possibility of electrical pumping. These advantages enable the organic semiconductors great scientific interest and technological significance, and so much research has been reported on the organic semiconductor lasers [12–17]. However, few reports have been devoted to the electrical control of the laser emission from organic semiconductors.

In earlier works [18], we have demonstrated a distributed feedback (DFB) organic semiconductor laser based on a holographic polymer dispersed liquid crystal (HPDLC) grating acting as an external feedback structure. Stable single-mode transverse electric (TE)-polarized laser emission was obtained under optical pumping. The use of HPDLC grating empowered by one-step holography technique results in low-cost and simple fabrication, rapid and large-area device prototyping and capability of electrical control because of the introduction of LC [18–23]. In this paper, to the best of our knowledge, we report the electrical control of the DFB organic semiconductor laser based on a HPDLC grating for the first time. The experimental results show that the lasing intensity can be modulated by increasing the electric field from 0 to 15.0 V/μm.

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During the modulation process, the lasing wavelength is found a good stability with a slight blue-shift of 1.4 nm. These results are attributed to the decreases in the refractive index modulation and average refractive index of the HPDLC grating respectively, which are induced by the reorientation of LC molecules under external electric field.

2. Experiments

Fig. 1 shows the schematic structure of the controllable DFB organic semiconductor laser. A HPDLC grating is located on the top of an organic semiconductor poly(2-methoxy-5-(2′-ethyl-hexyloxy)-p-phenylenevinylene) (MEH-PPV, Jilin OLED Material Tech.) film between two indium-tin-oxide (ITO)-coated glass substrates. To acquire that structure, an empty cell was pre-fabricated by combining one glass substrate coated with MEH-PPV and the other one with polyimide (PI) film to align LC molecules, which was rubbed unidirectionally parallel to z axis (Fig. 1) corresponding to the groove direction of HPDLC grating. The MEH-PPV film was formed by spin-coating in a xylene solution (6 mg/mL) and its thickness was fixed at 80 nm by selecting appropriate rotation speed. Mylar spacers with a thickness of 6 μm were placed between the two substrates to control the cell gap. Then a uniform mixture of HPDLC pre-polymer syrup, consisting of difunctional acrylate monomer phthalic diglycol diacrylate (PDDA, 54.6 wt%, Sigma–Aldrich), LC TEB30A (33.0 wt%, $n_o = 1.522$, $n_e = 1.692$, Slichem) and photo-initiators (12.4 wt%), was injected and diffused into the entire cell via capillary action in the dark. The refractive index of the pure polymer formed by monomer PDDA was measured to be 1.525 by Abbe refractometer. The detailed materials composition of the photo-initiators can be found elsewhere [4]. After that, the sample cell was exposed to an interference pattern created by two coherent s-polarized laser beams from a 532 nm Nd:YAG laser. A HPDLC grating with periodic alternating LC and polymer layers was obtained via photo-polymerization after 5 min exposure. The wavelength λ_{las} of the DFB laser emission is determined by the grating period Λ, the effective refractive index n_{eff} of laser mode and the Bragg order m [24]:

$$\lambda_{las} = \frac{2n_{eff}\Lambda}{m}. \tag{1}$$

Considering that the n_{eff} of the laser mode from our DFB structure was about 1.60 [18], the grating period was carefully chosen as 395.2 nm to generate a second-order DFB laser with a wavelength around 630 nm located in the gain spectrum of MEH-PPV [13].

To determine the LC molecules orientation in the HPDLC grating, s- and p-polarized lights at 633 nm, generated by a combination of a He–Ne laser and a polarizer, were incident on the grating at the Bragg angle to measure the diffraction efficiency during the grating forming process, as described earlier [25]. Here, we note some direction issues for clarity that the s-polarized light and TE light have the same polarization state parallel to z axis, while the polarization state of p-polarized light is parallel to y axis.

As an optical pumping source for laser measurements, a 532 nm Q-switched Nd:YAG pulsed laser with 8 ns pulse duration and 3 Hz repetition rate was used. A cylindrical lens was applied to focus the pumping laser onto the sample with an incident angle of 60° relative to the glass substrate. The pumping beam shaped by an adjustable slit was about 3 mm in length and 0.1 mm in width. Under optical pumping, laser emission from the sample due to the second-order DFB effect [12,14] was collected along the sample normal by a fiber-coupled spectrometer (resolution: 0.2 nm). Since the output intensity of the pulsed pumping laser was not stable, the laser emission spectrum was measured 10 times under each pumping condition and an average result was presented in this paper to minimize the error. A square-wave voltage of 1 KHz frequency was output by a signal generator and applied on the sample to control the DFB laser emission.

3. Results and discussion

To better understand the electrical controllable performance of the DFB organic semiconductor laser, the orientation of LC molecules in the HPDLC grating needs to be identified first. The HPDLC grating studied here consists of two parts [25]: one is the polymer matrix with some trapped LC molecules which are randomly aligned and not free to rotate by external electric field [26], and the other is the pure LC layer in which the LC molecules orientation has a significant effect on the diffraction efficiency of HPDLC grating. Since the refractive index of pure polymer n_p (1.525) is more closer to n_o (1.522) rather than n_e (1.692), a higher diffraction efficiency can be obtained for the probe light with a polarization state parallel to the long axis of LC molecule which “sees” a refractive index of n_e. Fig. 2 shows the real-time diffraction efficiency of the grating for the s- and p-polarized probe lights. When the HPDLC grating is achieved, the diffraction efficiency for s-polarization is 44% higher than the one for p-polarization of 3%, which suggests that the orientation of LC molecules is preferentially parallel to the s-polarization state, that is, the grating groove (z axis). It is worth noting that the LC molecules orientation obtained in this experiment is different from our previous report [25], in which the LC molecules orientation is parallel to the grating vector (y axis). The reason for

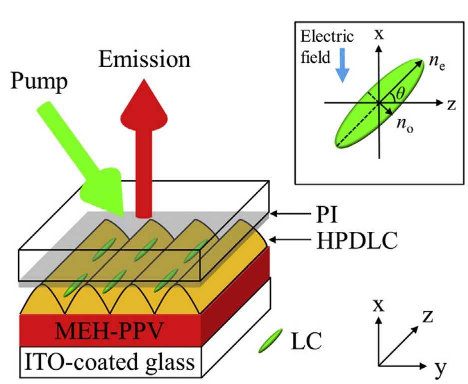

Fig. 1. Schematic structure of the DFB organic semiconductor laser. The inset shows the tilt angle θ of LC molecule under an electric field.

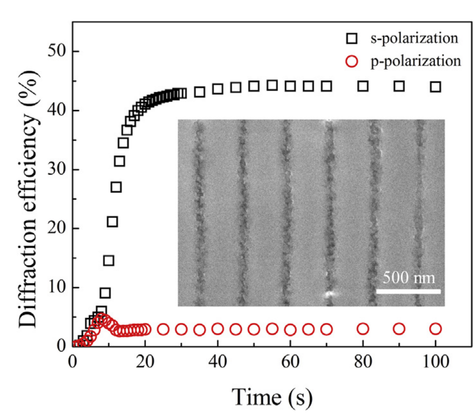

Fig. 2. The real-time diffraction efficiency for different polarizations. The inset shows the SEM image of the HPDLC grating.