Organic Electronics 38 (2016) 238–244

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Nearly diffraction-limited conjugated polymer microlasers utilizing two-dimensional distributed Bragg resonators

Wenbin Huang [a, b, c], Donglin Pu [a, b], Wen Qiao [a, b], Zongbao Fang [a, b], Xiaohong Zhou [a, b], Yan Ye [a, b], Guojun Wei [a, b], Yanhua Liu [a, b, *], Linsen Chen [a, b, c, **]

[a] College of Physics, Optoelectronics and Energy & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou, 215006, China

[b] Key Lab of Advanced Optical Manufacturing Technologies of Jiangsu Province & Key Lab of Modern Optical Technologies of Education Ministry of China, Soochow University, Suzhou, 215006, China

[c] SVG Optronics, Co., Ltd, Suzhou 215026, China

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form
20 August 2016
Accepted 25 August 2016

Keywords:
Microcavities
Light-emitting polymers
Holographic interferometry
Vertical emitting lasers
Laser arrays

ABSTRACT

We report nearly diffraction-limited lasing from the two-dimensional distributed Bragg reflector (DBR) resonator with a conjugated polymer layer as the gain medium. The resonator consists of four Bragg mirrors, which are fabricated by dot-matrix holography. The in-plane optical confinement in this cavity is achieved via two-dimensional Bragg reflections and the vertical confinement is provided through total internal reflection at the slab interface, leading to a three-dimensional confinement of the emitter. Upon optical pumping, the cavity emits nearly diffraction limited laser emission perpendicular to the surface with a threshold of 9 μJ/cm^2 and a bandwidth of 0.31 nm which is quite advantageous to its one-dimensional counterpart. Facile fabrication of two-dimensional DBR polymer lasers with different parameters by dot-matrix holography was also demonstrated. It was further found that the cavity Q factor decreases by a factor of two and the laser threshold increases to 0.41 mJ/cm^2 when the mirror size decreases to 20 μm. Our results indicate a step towards the application of polymer micro-lasers in the fields of displays and spectroscopic analyzing.

1. Introduction

Microcavity lasers with advantages of excellent device performance, simple fabrication and wide wavelength tunability are of great interest, as they are important constituting components in photonic integrated circuits to realize on-chip optical processing, parallel interconnection, imaging and sensing [1,2]. To this regard, the use of the organic semiconductor as the gain medium is expected to be a feasible approach. Organic semiconductors have a number of advantages, such as large stimulated emission cross-sections, broadband and programmable gain spectra, solution processibility and compatibility with virtually all substrates [3–5]. Moreover, they are rich in natural resources and mechanically flexible which are important to realize low-cost and even disposable micro-lasers for flexible optoelectronics. To date, various resonator configurations have been explored to fabricate organic semiconductor lasers, including distributed feedback (DFB) gratings, Fabry–Pérot (FP) microcavities, whispering gallery mode (WGM) resonators and photonic crystals [3]. The DFB cavity may be the most intensively investigated configuration due to its easy fabrication, low working threshold and strong mode selection capability [3]. However, the active film in a DFB polymer laser is periodically corrugated which makes the incorporation of electrodes and transport of charge carriers through the film difficult, hindering the realization of electrically injected polymer lasers. The FP microcavity, which is also known as the planar microcavity or the organic vertical cavity surface emitting laser, consists of a planar sandwich of the active film between two reflecting mirrors [6,7]. In the direction perpendicular to the film plane, standing waves are formed which provide positive optical feedback for lasing. The first demonstration of lasing from the solid-state

* Corresponding author. College of Physics, Optoelectronics and Energy & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou, 215006, China.

** Corresponding author. College of Physics, Optoelectronics and Energy & Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou, 215006, China.

E-mail addresses: yhliu@suda.edu.cn (Y. Liu), lschen@suda.edu.cn (L. Chen).

http://dx.doi.org/10.1016/j.orgel.2016.08.024
1566-1199/

conjugated polymer was also based on this cavity [7]. Common metallic mirrors could be employed as the reflecting components or they can be replaced with dielectric Bragg mirrors for higher cavity Q values.

Main advantages of FP microcavities include high device compactness, intense localization of photons in the cavity, and ease for the injection of electrical carriers through the homogeneous active film. They can be fabricated by direct deposition of the metallic or dielectric Bragg mirror onto the organic material with another mirror as the bottom substrate or melting together two mirrors with active films on them beforehand. Sophisticated vacuum equipment and extensive fabrication time are required in these processes. Oxidation of the organic material during deposition may occur which quenches its stimulated emission. These problems can be partly resolved by spin coating alternating thin layers with different refractive indices to obtain the Bragg mirror [8]. Apart from the fabrication complexity, the demonstrated working threshold of FP microcavity polymer lasers is high which is often above 10^3 kW/cm^2 [9,10]. This is attributed to the short interaction length of the light field with the gain medium. An alternative approach to the FP resonator is to arrange the resonator axis parallel to the film plane. In such a configuration, light is waveguided in the high refractive index active film and forms standing waves between two end mirrors [11]. Low working thresholds have been demonstrated due to its long interaction length [12]. Initially, end mirrors are obtained by simply cleaving the organic film edges. This edge-emitting configuration suffers from highly divergent lasing because of the subwavelength size of the output aperture. In order to solve this, Bragg mirrors are employed and surface-emitting lasers have been realized due to the outcoupling effect of the periodic structure [13–15]. To differ from the FP microcavity structure, this device was referred to as the distributed Bragg reflector (DBR) polymer laser. To date, only one-dimensional (1D) DBR polymer lasers have been realized. As photons are two-dimensionally (2D) confined in the plane perpendicular to the film, its cavity Q factor is not very high and the output laser pattern is highly divergent in the direction along grating grooves [16].

In this paper, we demonstrate 2D DBR polymer lasers with nearly diffraction limited output emission. The conjugated polymer film was surrounded by four Bragg mirrors. The in-plane confinement by 2D Bragg reflections and the vertical confinement by total internal reflection at the slab interface lead to a three-dimensional (3D) confinement of photons. These Bragg mirrors or grating pixels are fabricated with the dot-matrix holography technique. Each Bragg mirror was completed within single laser pulse, and facile fabrication of arrayed 2D DBR polymer microlasers (5 × 7) is demonstrated. Apart from the reduction in the divergent angle of the output emission, the cavity Q factor and the working threshold in this 2D cavity are significantly improved as compared to the 1D counterpart. We also investigated the effect of the Bragg mirror size on device performance. It is found that the cavity Q factor and the working threshold hardly change when the mirror size decreases from 160 μm to 40 μm. However, an abrupt deterioration in device performance is observed when the mirror size decreases to 20 μm. The combination of high device performance with the low-cost and efficient fabrication process indicates a step towards on-chip application of these tiny, coherent optical sources.

2. Experimental details

The working configuration of the 2D DBR polymer laser is schematically shown in Fig. 1(a). The planar polymer film which acts as the amplifier is surrounded by four Bragg mirrors. When the film center is optically pumped, emitted photons are waveguided in the high refractive index film and form standing waves in the film plane due to reflections from the four gratings. If the 2th Bragg grating is employed, light resonating in the film plane would be scattered normal to the surface, forming a surface-emitting polymer microlaser. Photons are three dimensionally confined in the cavity and diffraction-limited emission can be obtained. In addition, improvements in the cavity Q value and the working threshold are anticipated due to a better confinement of photons. In order to fabricate the device, four subwavelength gratings are required with well-defined size and position parameters. Conventional interferometric lithography could effectively fabricate subwavelength gratings but the grating size and location cannot be precisely controlled. On the contrary, electron beam lithography could provide gratings with precisely controlled parameters but suffer from extremely long operation time. In order to overcome these limitations, we have employed dot-matrix holography to complete this task. The configuration of the self-made dot-matrix holography equipment is schematically shown in Fig. 1(b). The spatial light modulator (SLM, Digital micromirror device, 0.7″ with a pixel size of 13.68 μm) was illuminated by the expanded beam from a compact laser at 351 nm with a repetition rate of 1 kHz and a pulsed of 15 ns (Advanced Optowave Corporation). After passing through the 4f coherent imaging system, the laser beam image was directed upon a diffraction grating and only ±1 orders of diffracted beams are allowed to pass through the objective lens. The focused spot created by the interference of the two diffracted laser beams was used to write the grating pixel into the photoresist. As the focused spot is a demagnified image of that on the SLM, the size and the shape of each grating pixel can be dynamically controlled by refreshing the SLM. Considering the demagnification M of the objection lens is 20, the length and the width of one grating pixel could be set within (5 μm, 700 μm) and (5 μm, 500 μm) with an error of 0.7 μm, respectively. The grating period Λ of the Bragg micro-mirror follows the simple mathematical equation of $\Lambda = \Lambda_0/2M$, where Λ_0 is the period of the diffraction grating. The orientation of each grating pixel could be adjusted by rotating the diffraction grating. In addition, the stage is driven by a micro-stepping controller and advances in the X-Y plane (±1 μm) to spatially distribute grating pixels as monitored by a computer. One grating pixel requires a single pulse laser exposure and recording takes place in accordance with stage positioning, thus this technique offers both high flexibility and efficiency for fabricating DBR polymer lasers.

In order to obtain surface-emitting lasing around 610 nm, the pitch of the diffraction grating is chosen to be 16 μm which yields a period of 400 nm in resultant grating pixels. Each 2D DBR polymer laser consists of four grating pixels and 5 × 7 microcavities are designed for each sample. Three samples were made in which the Bragg mirror size is 160 μm, 80 μm and 20 μm, respectively. The self-made dot-matrix holography equipment could complete the lithography task in several minutes. These specifically distributed grating pixels were first defined in the positive photoresist (RZJ390, Suzhou Ruihong Co., Ltd.). The developed pattern was then transferred to the silica substrate by reactive ion etching (Tegal, 901e). The grating depth was between 30 nm and 50 nm for all samples. Fig. 1(c) shows the scanning electron microscopy (SEM) image of the 2D DBR cavity where Bragg mirror size is 20 μm. As designed, a planar square is surrounded by four Bragg mirrors. The displacement for each grating pixel is less than 2 μm which is negligible as compared with the cavity size. The appearance of the grating region is not very homogeneous. This is due to the inhomogeneous development of the photoresist as a result of the non-uniform focusing spots. Further improvements in optical path design could solve this shortcoming. Fig. 1(d) is an SEM image at a higher magnification showing details of the grating. Although some