Low threshold edge emitting polymer distributed feedback laser based on a square lattice

A. E. Vasdekis, G. A. Turnbull, and I. D. W. Samuel
Organic Semiconductor Centre and Ultrafast Photonics Collaboration, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife KY16 9SS, United Kingdom

P. Andrew and W. L. Barnes
Thin Film Photonics Group, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom

(Received 9 November 2004; accepted 21 February 2005; published online 11 April 2005)

We report the demonstration of a low-threshold, edge-emitting polymer distributed feedback laser based on a square lattice. The lattice constant was 268 nm, which corresponds to a lattice line spacing in the \( \Gamma M \) symmetry direction of the Brillouin zone of 189 nm. The latter was employed to provide feedback at 630 nm via a first order diffraction process. The device operated on two longitudinal modes, which were situated on the band-edge near the \( M \) symmetry point. The two modes had thresholds of 0.66 nJ and 1.2 nJ—significantly lower than comparable surface-emitting DFB lasers. Angle dependent photoluminescence experiments were performed to investigate the effect of the square lattice on the laser operation and the origin of the low threshold. © 2005 American Institute of Physics. [DOI: 10.1063/1.1898430]

Conjugated polymers have attracted considerable interest during the past decade because they possess both functional photophysical properties and simple device fabrication. Their strong absorption and broadband emission are two characteristics that make them ideal candidates for solid-state lasers in the visible spectral range.\(^{1,2}\) To this end, multiple resonator configurations have been suggested, such as microcavities,\(^{3}\) microdisk lasers,\(^{4}\) and distributed feedback (DFB) structures.\(^{5-10}\) The latter are particularly attractive as they combine low threshold operation and well defined output beam, with the possibility of simple fabrication.\(^{5}\)

A generic schematic of a DFB polymer laser is shown in Fig. 1(a). A corrugated conjugated polymer acts as both gain medium and resonator, and is optically pumped. The operation of such a structure is based on the periodic modulation of the refractive index, which is responsible for the formation of a standing wave (Bloch mode\(^{11}\)) through interference effects in the plane of the polymer film. The mode is additionally confined in the plane of the propagation direction via total internal reflection. The refractive index periodicity can either be one or two-dimensional, resulting in single or multiple resonance axes, respectively. Doubly periodic organic lasers have been investigated, employing either a hexagonal\(^{9}\) or square lattice.\(^{7}\) The advantages of the two-dimensional periodicity are higher gain and more coherent output modes.

To date, polymer lasers based on square feedback lattices have employed an optical periodicity (lattice constant multiplied by the effective refractive index of the optical mode) equal to the lasing wavelength, so that feedback is provided by second order diffraction from the grating. These structures operate at the \( \Gamma \) point of the Brillouin zone and have the advantage of being surface emitting, though this simultaneously imposes extensive scattering losses stemming from coupling to free space radiation. In this letter, we show that a different symmetry of the Brillouin zone of a square lattice can be used, producing an edge-emitting laser with lower threshold.

For the case of a square lattice, there are two mirror lines defined by the Miller indices \((10)\) and \((11)\), oriented at an angle \( \Phi=45^\circ \) with respect to each other [Fig. 1(b)]. In the corresponding Fourier space representation there are two reciprocal lattice vectors, each of which could satisfy the Laue condition, and thus provide feedback for a particular incident wavevector.\(^{12}\) In Fig. 1(b) the two vectors are denoted as \( G_1 \) and \( G_2 \) and point along the two symmetries of the Brillouin zone.

FIG. 1. (a) Cross-sectional view of a 2D DFB polymer laser; the angles \( \theta \) (polar angle to the \( z \) axis) and \( \Phi \) (azimuthal angle in the \( x-y \) plane) correspond to the direction of emission and the symmetries of the Brillouin zone (the \( \Gamma X \) for \( \Phi=0^\circ \) and the \( \Gamma M \) for \( \Phi=45^\circ \) respectively); (b) the real space lattice of the square diffraction grating. The mirror planes \((10)\) and \((11)\) are illustrated, along with the grating vectors \((G_1, G_2)\) for the two symmetries of the Brillouin zone.
that produced 1 ns pulses. The beam was focused to a spot of \( \mu \) of Fig. 2, was found to be most intense at 

In Fig. 2, the output spectra as a function of the pump energy for the two longitudinal modes

The two lasing modes correspond to different Bloch modes that satisfy the Bragg condition for a lattice constant of 189 nm (\( \Gamma M \)). They differ in spatial localization with respect to the grating planes and hence are characterized by different effective refractive indices. The asymmetry in gain and loss, associated with the different spatial distributions of the optical field in each mode, is responsible for their different thresholds. The lower wavelength mode has a lower effective refractive index as it is localized on a lower refractive index region, suffering both from intrinsically poorer waveguiding and less amplification (see Fig. 4 for the experimental dispersion diagram). The observation of two-wavelength operation is different from other two-dimensional, vertical-emitting polymer DFB lasers, in which all the spatial harmonics of the lasing mode are coupled inside the air cone. In such lasers, there is strong discrimination between the two band-edge modes arising from different radiation losses and coupling strengths to free space radiation. Our observation of two-mode oscillation shows that the mechanism of strong mode discrimination is not present when operating below the light line (feedback occurring for in-plane wave vectors larger than \( \omega_{\text{pl}}/c \)).

In order to probe further the optical properties of the device, the spontaneous emission spectra were measured as a function of the angle of diffraction \( \theta \) in Fig. 1(a), an experiment that has been shown to reveal information about the propagation conditions and scattering losses of a mode that propagates in the periodic structure. In essence, due to momentum conservation in the plane of the film, the angle of

FIG. 2. Output spectra of the polymer laser above and below threshold. Inset shows a contour plot of the emission’s wavelength vs the angle \( \theta \) measured in the plane \( \Phi = 45^\circ \).

FIG. 3. Laser output as a function of pump energy for the two longitudinal modes

FIG. 4. Experimental and calculated values of the angle dependent photoluminescence measurements.

The threshold of this device was lower than the value of 4 nJ reported for a surface emitting polymer laser based on MEH-PPV, where a 65% deeper square lattice grating was used with a period of 409 nm. Two factors lead to the lower threshold operation of the current device. The first is the increased \( Q \)-factor of the resonant modes that is associated with the fulfillment of the Bragg condition below the light line and the second is the smaller spot size of the pump light used in this experiment.
planes normal to the photoluminescence experiment revealed that the grating measurements confirmed this, as in both measurements light emission and photoluminescence were observed. The angle of the polymer laser with a low threshold that is attributed to a high polymer film with a low threshold that is attributed to a high refractive index of the MEH-PPV film and the refractive indices of the propagating modes. For this calculation, the refractive indices of the MEH-PPV film and the substrate were measured by variable angle spectroscopic ellipsometry.

In conclusion, we have demonstrated an edge emitting polymer laser with a low threshold that is attributed to a high $Q$-factor of the resonant modes. The decreased losses were associated with the operation below the light line. For the same reason, two-mode oscillation was observed. The angle dependent laser emission and photoluminescence experiments confirmed this, as in both measurements light emission at the lasing wavelengths was edge coupled. Finally, the photoluminescence experiment revealed that the grating planes normal to the $\Gamma X$ symmetry direction contributed only to weak scattering losses, while the respective ones normal to the $\Gamma M$ direction that provided the feedback were responsible for a stop band and a reduced group velocity in the spectral region of the laser wavelength.

Fruitful discussions with Professor T. F. Krauss are respectfully acknowledged. We are grateful to EPSRC for financial support and to Covion for the supply of the polymer MEH-PPV. The assistance of Dr. C. Yates with the ellipsometry measurements is also gratefully acknowledged.