Effect of gain localization in circular-grating distributed feedback lasers

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We explore the influence of gain localization on the lasing performance of circular-grating distributed feedback (CDFB) lasers. The effect is studied in an optically pumped CDFB laser resonator based on a waveguide of the conjugated polymer poly[2-methoxy-5-(2’-ethylhexyloxy)-1,4-phenylene vinylene]. Variations in lasing threshold and slope efficiency are determined as a function of the radius of the optical excitation. The experimental lasing results are compared with predictions from a theoretical analysis based on an adaptation of the transfer matrix method. We find that a strong localization of the gain near the center of the CDFB laser can lead to both a substantial reduction in threshold and increase in output efficiency. As the excitation radius changes from a 90 to a 15 μm radius, the threshold energy decreases from 5.3 to 0.29 nJ, and the surface-emitted output efficiency increases by an order of magnitude. A simple model is developed that confirms that the significant reduction in threshold can be explained by an enhanced overlap of the population inversion with the resonant mode. © 2005 American Institute of Physics. [DOI: 10.1063/1.2120915]

There has been growing interest in recent years in semiconductor lasers based on two-dimensional distributed feedback (DFB) resonators. Various laser structures have been explored experimentally in both III–V and organic semiconductors, including photonic crystals,1–6 circular-grating DFB (CDFB),7–11 and quasicrystals.12 Such two-dimensional structures can significantly improve the operating characteristics of surface-emitting DFB lasers, compared with conventional one-dimensional gratings.4,5 They can lead to lower lasing thresholds, improved slope efficiencies, and near diffraction-limited output beams.

The improved laser performance derives from a multidirectional feedback defined by the rotational symmetry of the structure. While both photonic crystals and quasicrystals possess a discrete N-fold rotational symmetry, CDFB structures have complete circular symmetry about a unique center position. This means that CDFB lasers have an appealing feature that they can apply feedback in all directions in the plane. We and others have previously shown from theory that this leads to a strong localization of the resonant optical modes at the center of a CDFB resonator, even for gratings of modest index contrast.13,14 This effect is illustrated in Fig. 1, which shows the calculated radial dependence of the optical intensity in a polymer CDFB laser. The calculation, based on a transfer matrix method analysis, is described in detail in reference.14 The two curves represent the intensity envelopes of the lowest threshold even and odd radial modes of a CDFB structure corresponding to the experimental laser described later. The intensities have been scaled here by multiplying by the radial coordinate, and then normalized so that the total power in each mode is equal.

It is well known that the strength of stimulated emission in a laser medium depends on the product of the local optical intensity and population inversion density.15 One might therefore expect the stimulated emission to be strongest at the center of the CDFB structure. Furthermore, the significant variation in mode intensity should lead to a strong radial dependence of gain saturation for operation well above threshold.16 These factors suggest that there may be a significant advantage in concentrating the inversion near the center of the resonator, in order to optimize the light-matter interaction. Previous work on CDFB lasers has considered only uniform or large-radius Gaussian pump profiles (e.g., Refs. 7–11, 13, 14, 16, and 17). Of these, one study has predicted that a Gaussian pump, whose 1/e2 radius is a factor $\sqrt{2}$ smaller than the grating radius, should give a modest reduction in threshold compared with uniform pumping.17 A study of circular Bragg-reflector lasers, meanwhile, has calculated an optimum radius for the uniform central gain region.18 In this paper we demonstrate that by strongly localizing the gain near the center of a CDFB resonator one may simply and substantially improve laser performance, achieving both a

FIG. 1. Mode intensity of the lowest threshold even and odd radial modes, normalized for equal power within resonator. Inset: schematic polymer CDFB laser.
large reduction in threshold and increase in output efficiency.

The structure of our CDFB laser is shown schematically inset in Fig. 1. It consists of a semiconducting conjugated polymer film \{poly[2-methoxy-5-(2’-ethylhexyloxy)-1,4-phenylene vinylene]\}, of \(\sim 100\) nm average thickness, deposited on a corrugated silica substrate. The silica-polymer-air structure forms an asymmetric slab waveguide, designed only to support the lowest order transverse electric mode within the emission band of the polymer. The corrugated grating comprises a set of concentric circular grooves with an outer radius of 100 \(\mu\)m and central defect of 300 nm diameter. The grating profile is a radially periodic, square-wave structure of period 400 nm, depth 125 nm, and groove width equal to a quarter-period. The period was chosen to provide a second-order distributed feedback, with surface-emitted output coupling via first-order Bragg scattering. The grating pattern was defined by electron beam lithography on a Leica EBPG-5 Beamwriter at the University of Glasgow, using a poly(methylmethacrylate) resist layer coated on top of the silica substrate. A thin film of NiCr (30 nm) was used as a charge dissipation layer and removed prior to development using chrome etch. The pattern was subsequently transferred into the substrate via reactive ion etching using fluorine chemistry (CHF\(_3\)).

Immediately after fabrication, the polymer waveguide was transferred to a vacuum chamber in which it was held under a vacuum of \(\sim 10^{-4}\) mbar during the subsequent optical characterization. For the threshold measurements, the sample was excited at 532 nm by the second harmonic of a Nd:YVO\(_4\) microchip laser that generated pulses of 1 ns duration, at 5 kHz repetition rate. The pump laser output energy was varied using neutral density filters, and then focused to a circular spot of \(\sim 6\) \(\mu\)m radius. By translating the polymer laser along the pump beam axis it was possible to vary the excitation \(1/e^2\) radius from 6 to 100 \(\mu\)m. For each value of excitation radius, the pump beam was carefully centred on the grating in order to minimise the threshold. The spectral output from the laser was measured normal to the waveguide using a fiber-coupled CCD spectrometer. Output energies from the laser were measured using a calibrated silicon energy meter.

When pumped above threshold, the emission from the polymer laser narrowed to a single peak at 632 nm, of linewidth \(\sim 0.7\) nm (limited by the spectrometer resolution). Such single-frequency lasing is commonly observed in surface-emitting polymer DFB lasers.\(^4\)–\(^6\),\(^9\)–\(^11\) Figure 2 shows the dependence of threshold energy on the excitation radius (triangles represent experimental data). As the pumped region of the polymer film changed from 90 to 15 \(\mu\)m radius, we observed a rapid drop in threshold energy from 5.3 to 0.29 nJ. The decrease in threshold saturated for small excitation areas, while in other data sets we observed a sharp increase in threshold at the smallest diameters. The optimal energy characteristics of the laser, measured for an excitation radius of 15 \(\mu\)m, are shown inset to Fig. 2. The laser had a threshold of 0.29 nJ, among the lowest reported for polymer lasers, and a output slope efficiency (measured normal to the waveguide) of 2\%. This output efficiency was an order of magnitude higher than the value measured for an excitation radius of 90 \(\mu\)m.

These data clearly indicate that the localization of gain in the center of the CDFB structure can significantly improve the lasing characteristics. We now aim to account quantitatively for the substantial decrease in threshold. To do so, we consider the extent of the spatial overlap of the mode intensity with the population inversion.\(^1\)\(^5\)

First we define the spatial dependence of the pumping and mode distributions. The pump energy density \(\Lambda(r)\) may be written as

\[
\Lambda(r) = \frac{E_p}{\pi R^2} \lambda(r); \quad \int \lambda(r) dA = 1, \tag{1}
\]

where \(E_p\) is the pump pulse energy and we assume that \(\lambda(r)\) only varies radially in the plane of the CDFB grating. We define the intensity of a given radial mode of a grating of radius \(R\) as

\[
I = I_0 |u(r)|^2 |\phi(z)|^2, \quad 0 \leq r \leq R, \tag{2}
\]

in which we separate the spatial variations in the plane of, and perpendicular to, the waveguide and neglect azimuthal variations. We assume that the function \(u(r)\) is independent of \(\lambda(r)\), which is reasonable as index coupling is much stronger than gain coupling in our structures.\(^4\) The population inversion density \(N\) will also vary spatially, and below laser threshold \(N(r,z) \propto \Lambda(r)\).

Clearly, the rate of stimulated emission (\(\propto N\lambda\)) will vary strongly across the resonator. However, it can be shown that the threshold of the laser depends on the spatially averaged inversion density:\(^1\)\(^5\)

\[
\langle N \rangle_{\text{TH}} = \frac{\int_{\text{CDFB}} N(r,z)|u(r)|^2 |\phi(z)|^2 dV}{\int_{\text{CDFB}} |u(r)|^2 |\phi(z)|^2 dV}, \tag{3}
\]

where the integrals are calculated over the volume of the CDFB resonator. At laser threshold, the spatially averaged inversion \(\langle N \rangle_{\text{TH}}\) provides sufficient gain to overcome the fixed round-trip losses of the resonator.

It follows from Eqs. (1)–(3) that we can define a spatially averaged effective pump density \(\Lambda_{\text{TH}}\) that will establish the threshold inversion \(\langle N \rangle_{\text{TH}}\).

![FIG. 2. Measured laser threshold energies as a function of pump beam radius. Curve shows the calculated dependence of threshold on pump beam radius (normalized to the threshold under uniform pumping) for the lowest threshold odd radial mode. Inset shows measured energy characteristic for \(w = 15\) \(\mu\)m.](image-url)
of the grating.

we consider each radial mode independently, and so the higher output efficiency, since there would be a more enhanced inversion-mode overlap explains the significant reduction in threshold and increase in output efficiency. These effects can be accounted for quantitatively by considering the spatial overlap of the resonant mode and inversion density. The advantage of gain localization should be more widely applicable to other two-dimensional resonators, and lead to improved performance in semiconductor microlasers.

To conclude, we have shown that the pump focusing in a polymer CFB laser can have a significant impact on lasing characteristics. Strong localization of the gain near the centre of a CDFB laser can lead to both a substantial reduction in threshold and increase in output efficiency. These effects can be accounted for quantitatively by considering the spatial overlap of the resonant mode and inversion density. The advantage of gain localization should be more widely applicable to other two-dimensional resonators, and lead to improved performance in semiconductor microlasers.

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\[ \langle \Lambda \rangle_{\text{TH}} = \frac{E_p}{\pi w^2} \int_0^R \lambda(r) |u(r)|^2 \, rdr \]
\[ \int_0^R |u(r)|^2 \, rdr = \int_0^R \lambda(r) |u(r)|^2 \, rdr. \]