

Two-dimensional distributed feedback lasers using a broadband, red polyfluorene gain medium

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We report the fabrication of widely tuneable (627–702 nm) optically pumped two-dimensional distributed feedback polymer lasers that utilize a red-emission fluorene copolymer as the active gain medium. The lasers exhibit efficient, low threshold operation and emit highly directional output beams as a result of the enhanced two-dimensional photonic confinement provided by the employed resonator. Their emission and operating characteristics are described in detail. We demonstrate that the very wide spectral range ($\Delta\lambda \geq 75$ nm) over which these lasers can be systematically tuned is in very good agreement with theoretical predictions based on a simple waveguide model. In addition, we show that the lasers have long operating lifetimes $\tau_{1/2} \geq 2 \times 10^7$ pulses and we discuss the impact that degradation has on the laser output characteristics. © 2004 American Institute of Physics. [DOI: 10.1063/1.1811374]

I. INTRODUCTION

Following the outstanding progress towards commercialization of semiconducting polymer-based light emitting diodes and electroluminescent displays, significant attention is currently being paid to the development of these materials as novel gain media for devices such as lasers and optical amplifiers.^{1,2} Research in this field is partly driven by the effort to realize an electrically pumped solid-state polymer laser. Such organic laser diodes have the potential to be extremely versatile and cheap laser sources that may eventually compete with inorganic lasers in a number of fields. In particular, polymer diode lasers might offer the attractive characteristics of laser dyes (i.e., a very wide range of emission wavelengths, large tuning ranges, and low cost) with the robustness and practical applicability of inorganic diode lasers.^{3–8}

With regard to electrical pumping, a reduction in the lasing threshold of polymers is highly desirable, together with an improvement in charge carrier mobility. For the former, much emphasis is being placed on the identification and investigation of novel materials that show strong and efficient stimulated emission (with good charge transport properties also borne in mind), and their incorporation into optimized laser resonators.^{8–13} In this paper, we report a study of the red-emission Dow proprietary semiconducting fluorene copolymer known as Dow Red F. We demonstrate efficient laser oscillation in Dow Red F based resonators that provide enhanced, two-dimensional (2D) photonic confinement.

Dow Red F belongs to the increasingly important polyfluorene family of conjugated polymers. Polyfluorenes exhibit good gain characteristics combined with relatively good charge transport properties, and are therefore of strong potential interest for electrically driven laser devices.^{14–17} We have recently reported strong stimulated emission and broadband gain in Dow Red F slab waveguides, establishing this polymer as an attractive gain medium with which solid-state polymer lasers can be potentially fabricated.¹⁸ This statement is experimentally verified in the current paper with the successful realization of 2D distributed feedback (DFB) Dow Red F lasers.

The emission and operating characteristics of the Dow Red F lasers are described in detail. In addition to low threshold, efficient operation we show that the output wavelength of these devices can be systematically tuned across a very wide spectral range ($\Delta\lambda \geq 75$ nm). To date, this is the largest tuning range achieved from a conjugated polymer laser, highlighting the broadband gain available from Dow Red F. In addition, the measured data are found to be in excellent agreement with DFB laser theory. Finally, we discuss the operational lifetime and the impact that degradation has on the output characteristics of our lasers, information that is often absent from the literature but that is needed in order to start to assess the practicality of conjugated polymer lasers.

II. EXPERIMENT

The lasers were fabricated by depositing Dow Red F layers from 20 or 30 mg/ml toluene solutions on top of suitably microstructured fused silica substrates. The thickness of the polymer films was varied between ~150 and 600 nm by controlling the solution concentration and the rotation speed

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in the spincoating process. The devices employed crossed (two-dimensional) double grating microstructures as substrate corrugation patterns. These microstructures provide both resonant feedback and output coupling of the oscillating fields that are guided within the polymer layer.¹⁹ A standard lithographic fabrication process was employed in their fabrication: the substrate corrugations were initially defined holographically in photoresist layers coated on fused silica substrates; subsequent chemical development of the photoresist and reactive-ion etching into the silica plates, formed the final bi-grating structures. The silica/polymer/air structures constitute corrugated asymmetric waveguides that can support an increasing number of propagating transverse modes with increasing polymer layer thickness.

The period Λ of the gratings was selected for second-order DFB operation and was ~ 409 nm in both directions, while the groove depth was ~ 60 nm. In contrast to conventional single-grating DFB lasers, the bi-grating provides DFB laser structures with superior performance due to stronger photon confinement within the guiding gain region.^{8-10,20} Our devices can also be envisaged as photonic crystal polymer lasers.^{21,22}

The polymer laser structures were optically excited at $\lambda_{ex}=540$ nm (corresponding to the lowest energy absorption peak of Dow Red F) with 10 ns pulses from a Q -switched Nd:YAG (YAG—yttrium aluminum garnet) laser pumped type-II β -BaB₂O₄ optical parametric oscillator. The pump beam was incident upon the structures at $\sim 20^\circ$ to the surface normal and formed a rectangular spot of dimensions $\sim 250 \times 200 \mu\text{m}^2$. The energy of the pump pulses was controlled by a set of calibrated neutral density filters. The emission from the laser structures was collected normal to the waveguide surface using a fiber-coupled spectrograph equipped with a charge-coupled device (CCD) detector. The low threshold of our lasers also allowed optical pumping with a small microchip laser operating at 532 nm (~ 1 ns pulse duration), thus leading to very compact all-solid-state polymer laser systems. The transverse mode profile of the output beams from the polymer lasers was measured using a high-resolution laser beam diagnostics system (coherent beam-view analyzer).

III. RESULTS AND DISCUSSION

A. Operating characteristics

As noted earlier, our 2D-DFB polymer lasers utilize a bi-grating structure with an appropriate period selected for second-order operation. Hence, distributed feedback of the oscillating guided modes is provided through second-order Bragg scattering induced by the substrate corrugations, while these modes are coupled to radiation in a direction perpendicular to the substrate plane via first-order scattering.²³ Laser oscillation occurs near the Bragg resonance wavelength of the structures according to the relation (Ref. 24)

$$m\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda, \quad (1)$$

where m is the order of the grating ($m=2$ in our case), n_{eff} the effective refractive index of the waveguide, and Λ the corrugation period.

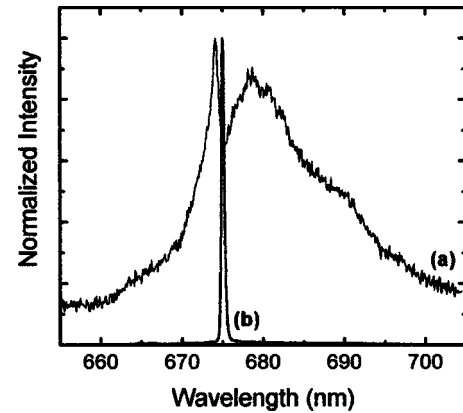


FIG. 1. Emission spectra of a Dow Red F 2D-DFB laser for excitation (a) below and (b) above the lasing threshold. The excitation wavelength was $\lambda_{ex}=532$ nm. The polymer laser operates at $\lambda_{DFB}=675$ nm.

Figure 1 shows the emission spectra of a Dow Red F 2D-DFB laser measured for emission parallel to the substrate normal, when pumped below [line (a)] and above [line (b)] its lasing threshold with the compact microchip laser. The subthreshold emission consists of the normal low intensity, broad Dow Red F photoluminescence but heavily modified by a pair of closely spaced Bragg scattered peaks. These peaks correspond to bound waveguide modes that have been coupled to free-space radiation at an angle normal to the substrate (polar angle $\theta=0^\circ$) by the fundamental component of the corrugation periodicity.^{19,25} They are separated by a characteristic sudden drop in emission intensity situated at the Bragg resonance wavelength of the structure ($\lambda=675$ nm in this case).

The sharp dip in emission intensity indicates the presence of a photonic stop band for waveguide modes and is induced by the bi-grating in the substrate.^{25,26} Here, second-order Bragg scattering effects become particularly important and maximum reflection of the guided field occurs. It is in this spectral region that laser oscillation is expected to occur and indeed, when the pump energy exceeds the threshold, the laser mode appears close to the Bragg dip wavelength and dominates the spectrum [line (b) in Fig. 1]. The laser linewidth was measured to be ~ 0.6 nm, limited by the resolution of our spectrometer.

The input-output characteristics of the 2D Dow Red F laser are presented in Fig. 2, which shows the dependence of the peak output intensity on the pump pulse energy ($\lambda_{ex}=532$ nm). A laser threshold of about 5 nJ (corresponding to an energy density of $10 \mu\text{J}/\text{cm}^2$) can be clearly observed in this plot. In the subthreshold regime, the emitted radiation corresponds to the normal polymer fluorescence and is weak. When the pump energy exceeds the threshold, an abrupt change in the slope of the input-output curve is observed, followed by a nearly linear increase of the output signal with increasing excitation energy. The relatively low oscillation threshold for this laser is in agreement with our previous observations of efficient deep-red stimulated emission in Dow Red F slab waveguides.¹⁸

The far-field transverse mode profile of the output beam from the 2D Dow Red F laser was measured by directing the beam onto a high-resolution CCD camera with no additional

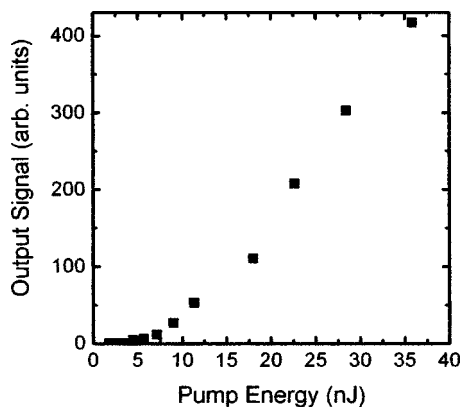


FIG. 2. Peak output intensity from the Dow Red F laser operating at $\lambda_{DFB} = 675$ nm as a function of pump pulse energy ($\lambda_{ex} = 532$ nm).

optics. The recorded output beam profile is shown in Fig. 3(a). The beam is annular in cross section with the laser mode almost symmetrical about the two grating axes, in contrast to the more divergent, fan shaped output beams typically obtained with standard 1D-DFB lasers.^{8,10} This is a direct result of the enhanced photonic confinement that is provided by the employed 2D crossed grating resonator. Another interesting observation is that the beam from the Dow Red F laser is azimuthally polarized, as clearly shown by the

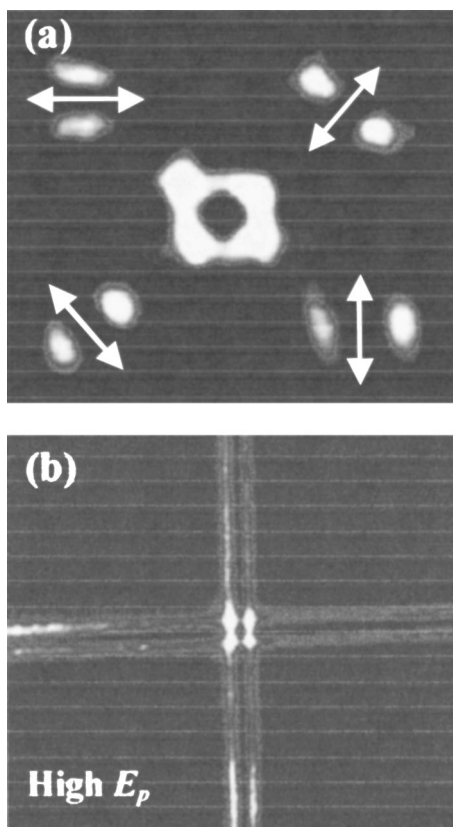


FIG. 3. (a) Transverse mode profile of the emitted beam from the 2D Dow Red F laser operating at $\lambda_{DFB} = 675$ nm ($\lambda_{ex} = 532$ nm). The four profiles surrounding the central annulus were obtained after passing the beam through a linear polarizer (polarization axis indicated by the white arrows). (b) Excitation of independent 1D resonances at high pump energies causes the beam shown in part (a) of this figure to acquire a more divergent cross-shaped profile.

four peripheral images in Fig. 3(a). These laser intensity distributions were obtained after passing the beam from the polymer laser through a linear polarizer (aligned with polarization axis as indicated by the double-headed arrows) and resemble the shape of a TEM_{01} mode whose axis rotates with the polarizer axis. This azimuthally polarized output beam is the result of a coherent summation of the two orthogonally polarized transverse modes that are inherently supported in this type of resonator.^{8,10,19,27} That this state of polarization exists is then a clear indication of the truly two-dimensional nature of the feedback in this laser. We note that 1D-DFB lasers emit strictly linearly polarized output beams.^{6,7,23,28} Finally, excitation at energies well above threshold results in the stimulation of independent uncoupled 1D resonances that produces two laser fans superimposed on the central highly directional spot. The beam then gradually acquires a more divergent, cross-shaped profile [Fig. 3(b) recorded at five times threshold], as also observed in other 2D-DFB lasers.^{9,10} The arms of the cross are each linearly polarized along their respective high-divergence axis, i.e., their polarizations are orthogonal to each other.

B. Wavelength tuning

One of the most interesting properties of semiconducting polymers with regard to their use as amplifying media is that they exhibit optical gain over broad spectral ranges and a selection of materials can together cover the entire visible spectrum. This offers potential for applications in highly tuneable lasers.^{20,29,30} To first approximation, the net gain spectrum of a conjugated polymer should follow its photoluminescence (PL) spectrum filtered by any residual self-absorption. Dow Red F exhibits minimal self-absorption losses and its PL is very broad, covering an extensive range in the red spectral region, namely from 580 to 850 nm.^{14,18} Hence, it is expected that Dow Red F will prove suitable for the fabrication of tuneable solid-state polymer lasers. In addition, we have recently shown that the maximum amplification wavelength in Dow Red F slab waveguides can be modified by controlling the structural properties of the guides, and in particular via mode cutoff methods.¹⁸ Though crude, waveguide cutoff methods provide a useful indication of the existence of broadband gain and are the only way to tune the stimulated emission position in such slab waveguide structures (without having to modify the gain medium itself), as confinement is achieved only in the lateral (normal to substrate) direction and no cavity feedback is involved.

In contrast, the 2D-DFB structures employed here provide a much more effective way of controlling the emission properties of the polymer. In particular, laser oscillation is strictly fixed close to the wavelength that satisfies the Bragg condition (1). Hence, modification of the structural properties of the DFB cavity (i.e., the bi-grating period and/or the effective refractive index of the guide) alters the supported resonant frequency and tunes the laser output, provided there is enough polymer gain for sustained oscillation at each new frequency. The effective refractive index n_{eff} of the waveguide arises because the guided mode propagates not only in the active polymer core but also spreads into the surrounding

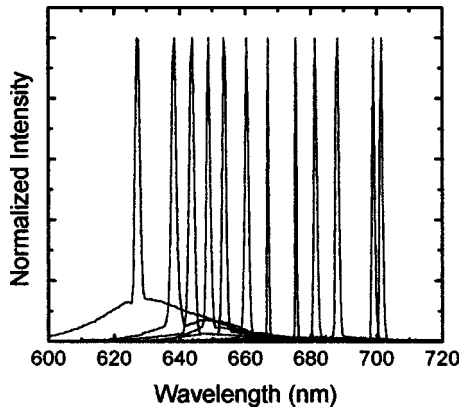


FIG. 4. Output spectra from Dow Red F based polymer lasers spanning 627–702 nm ($\lambda_{ex}=540$ nm). The polymer layer thickness in these structures ranged from ~ 150 to 600 nm. (Some laser lines appear narrower as they were recorded with a slightly higher-resolution spectrometer.)

cladding layers.³¹ The value of n_{eff} depends on the thickness and refractive indices of the layers that comprise the waveguide, and varies for different propagating modes (i.e., TE_0 , TM_0, \dots). For a specific mode of a polymer waveguide with fixed optical constants, the value of the effective refractive index experienced by the mode increases with increasing polymer layer thickness and is bounded by $n_s < n_{eff} < n_p$, where n_s and n_p are the refractive indices of the substrate and the polymer, respectively.³¹ Hence, to examine the tuneability of the Dow Red F lasers, we have fabricated a range of structures in which the thickness of the polymer layer was varied between ~ 150 and 600 nm. All lasers were photo-pumped at $\lambda_{ex}=540$ nm and utilized the 409 nm period bi-grating structure discussed in the preceding paragraph as the substrate corrugation pattern.

Figure 4 shows a series of laser lines obtained from the red polymer lasers. It is seen that the operating wavelength can be adjusted within a very broad spectral range, namely, $\Delta\lambda=75$ nm (from $\lambda=627$ to 702 nm). To date, this is the largest tuning range reported for a conjugated polymer laser. These results, together with our recent demonstration of a ~ 40 nm tuning range in the blue spectral region in lasers based on the homopolymer poly(9,9-dioctylfluorene),¹⁰ highlight the broadband gain that is accessible with polyfluorene materials and the potential of semiconducting polymers, in general, for the fabrication of widely tuneable laser sources.

Figure 5 shows the thresholds of the Dow Red F lasers as a function of emission wavelength calculated from the corresponding input-output curves. It can be seen that the lowest lasing threshold obtained is only ~ 0.55 nJ ($1.1 \mu\text{J}/\text{cm}^2$) for operation at $\lambda=698$ nm, while the thresholds rise steeply as the lasing wavelength is tuned away from this point. Varying the thickness of the active Dow Red F layer allowed the laser wavelength to be tuned from 634.5 to 702 nm (more details are reported below). Oscillation was not achieved outside this region even though Bragg scattered peaks were still visible in the emission spectrum. The threshold of the lasers increased dramatically as the emission was tuned towards the blue edge of the tuning range. At the limiting case of $\lambda=634.5$ nm the lasers had a threshold of $\sim 1.3 \mu\text{J}$ ($2.6 \text{ mJ}/\text{cm}^2$) compared to

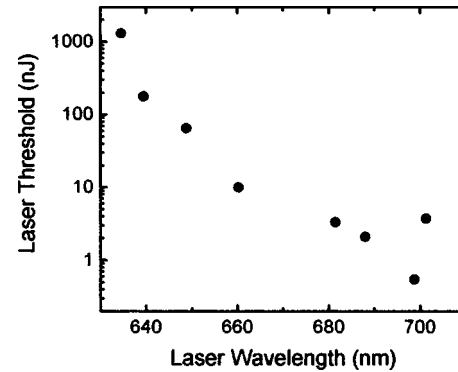


FIG. 5. Threshold energies (E_{th}) of the tuneable Dow Red F lasers as a function of oscillation wavelength ($\lambda_{ex}=540$ nm).

$\sim 0.17 \mu\text{J}$ ($340 \mu\text{J}/\text{cm}^2$) for $\lambda=639$ nm and only 0.55 nJ ($1.1 \mu\text{J}/\text{cm}^2$) for 698 nm, i.e., some two thousand times lower. The increase in the threshold of the shorter wavelength lasers is also evident in the increasing proportion of residual spontaneous emission seen in the corresponding output emission spectra (cf. Fig. 4).

A straightforward explanation for this behavior lies in the fact that as the emission wavelength approaches the edge of the available gain spectrum the oscillating fields experience less gain per round trip, while at the same time the self-absorption losses become larger. Another factor that imposes an adverse effect on the performance of the shorter wavelength lasers is the reduced guided mode confinement that these structures exhibit. In particular, tuning to shorter wavelengths is achieved by making the Dow Red F layer thinner and this results in a less confined mode that increasingly penetrates into the passive cladding layers.^{23,31} This in turn reduces the effective gain experienced by the mode and in combination with the lower material gain and increased self-absorption losses at shorter wavelengths, leads to the observed rapid increase in threshold.

The situation of increased oscillation thresholds at shorter wavelengths can be greatly improved by actively modifying the composition of the gain medium through use of appropriate poly(9,9-dioctylfluorene-*co*-benzothiadiazole) (F8BT)/Dow Red F blends. This dispersion of Dow Red F in F8BT shifts the net gain spectrum of Dow Red F to shorter wavelengths (depending on blend composition) and allows for lower threshold operation at shorter wavelengths.¹⁸ For example, in a 30 wt % Dow Red F blend structure, lasing was obtained at 643 nm with a threshold of ~ 22 nJ ($44 \mu\text{J}/\text{cm}^2$), namely, some six times less than for pure Dow Red F lasing at an equivalent wavelength. The employment of Dow Red F blends also allows for laser operation at even shorter wavelengths, extending the available tuning range down to at least 627 nm (cf. Fig. 4). Further experiments on polymer blend DFB lasers are the subject of ongoing research. It is anticipated that the blue end of the tuning range of the Dow Red F lasers can be further extended by appropriately utilizing the various F8BT/Dow Red F blends that can be fabricated.

In addition, since the Dow Red F photoluminescence extends to wavelengths well beyond 700 nm,¹⁸ we expect that these red lasers can be made to emit at even longer

wavelengths than presented here. This could be accomplished by using grating structures of longer period than the one employed here, so that the desired output wavelength can be achieved for sufficiently thin gain layers to avoid oscillation of higher-order modes.²⁸ Indeed, in our structures with thick (>450 nm) polymer layers that operated close to $\lambda=700$ nm, we observed multilongitudinal mode lasing at high excitation intensities. At low pump energies these lasers operate only in the transverse-electric (TE_0) mode. However, as the excitation is gradually increased, higher-order modes (that have higher threshold energies) start to oscillate. A sudden drop in the differential slope efficiency for the TE_0 mode is then observed, as a fraction of the inverted population starts to feed the added oscillation modes. This illustrates nicely the unfavorable impact of thick polymer layers on laser performance, and clearly shows that tuning solely through effective refractive index variation tends to be limited to a subset of wavelengths available from the full gain spectrum of the polymer. As noted already, for efficient single-mode operation at wavelengths beyond $\lambda=700$ nm, gratings with a longer period than that employed here should be used.

Finally, it should be noted that the broadband wavelength tuning of the red polymer lasers was found to be in excellent agreement with the relevant waveguide theory. A comprehensive description of the supported modes in our lasers would require a solution of Maxwell's equations for these complex 2D structures. However, for the experiments reported in this paper it is sufficient to follow a much simpler ray-optics approach, and in particular, to focus on the self-consistency condition for guided wave propagation. This condition simply states that the lateral component of the field that is guided through the polymer core must form a standing wave between the two cladding layers, and for our three-layer structures it can be written as:³¹

$$2kn_p h \cos \theta = 2\phi_s + 2\phi_a + 2m\pi, \quad (2)$$

where k is the wavevector of the propagating mode, h is the polymer layer thickness, θ is the mode propagation angle, ϕ_a and ϕ_s are the phase shifts due to total internal reflection at the polymer-air and polymer-substrate boundaries respectively (or the Goos-Hänchen shifts), and m is an integer which indicates the mode number. Condition (2) is a transcendental equation in θ and was numerically evaluated for Dow Red F slab structures with polymer layer thickness ranging from 0 to 800 nm. This allowed the determination of the corresponding waveguide dispersion diagrams and hence, the thickness dependent effective refractive index for the supported guided modes was obtained.^{20,23} The simple model employed here does not account for the wavelength dependence of the polymer refractive index n_p but this is expected to be relatively weak as the lasing wavelengths are well away from the absorption edge.

Assuming that the bi-grating in the substrates does not significantly modify the mode structure of the waveguides one can then calculate the dependence of the laser wavelength on polymer layer thickness. These data are shown in Fig. 6 (solid line) together with the experimentally determined oscillation wavelengths for the tuneable Dow Red F

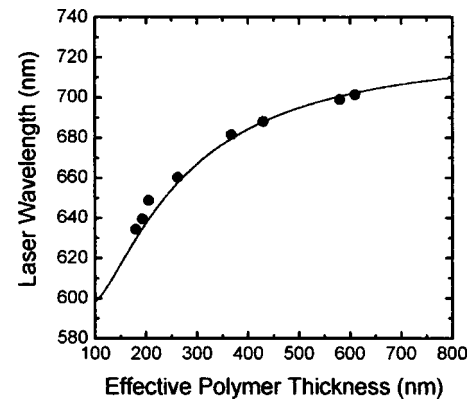


FIG. 6. Operating wavelength (λ_{DFB}) of the Dow Red F lasers as a function of effective polymer layer thickness ($d_{eff}=d+t/2$, where t is the grating depth): Experimental data (filled circles) and theoretical prediction (solid line).

lasers. The theoretical curve is for the fundamental TE_0 mode and was calculated using $n_a=1$, $n_p=1.77$, and $n_s=1.46$. To account for the (periodic) perturbation in the polymer layer thickness due to the substrate corrugations an effective polymer layer thickness was used, given by $d_{eff}=d+t/2$, where t is the grating depth.²⁸ It can be seen that despite the simplifications of the model the experimental data match very well with the theoretical predictions, demonstrating that the emission properties from these polymer lasers can be systematically controlled and modified.

C. Angle-dependent emission measurements

The emission from the Dow Red F lasers was analyzed as a function of wavelength and observation (scattering) angle for excitation powers both below and above the oscillation threshold.

Figure 7(a) shows the angle-resolved, TE polarized photoluminescence within the $\varphi=0^\circ$ azimuthal plane from a Dow Red F laser structure that supported oscillation at ~ 665 nm. Similar plots were obtained for all other red lasers. The shape of this graph matches very well with the theoretically predicted dispersion diagram of a DFB structure,²⁴ and is similar to those reported for other polymer DFB lasers.^{7,19,32} It can be seen that the change in wavelength of the Bragg scattered emission peaks produces two distinct branches that at normal incidence anticross around the resonant wavelength of the structure. These peaks correspond to bound waveguide modes that have been scattered out of the structure by the fundamental component of the corrugation periodicity. As already noted, at the Bragg resonance wavelength maximum backscattering of the corresponding guided modes occurs and a photonic stop band is produced. This effect is, however, not easily resolved in the present figure (although clearly shown in Fig. 1) as the spectra are quite noisy due to the very low intensity excitation that had to be employed in the angle-dependent PL measurements to remain well below the lasing threshold.

The angular pattern of the emission changes drastically when the excitation intensity exceeds the threshold [Fig. 7(b)]. Laser oscillation occurs and an intense, narrow peak replaces the broad modulated photoluminescence features of

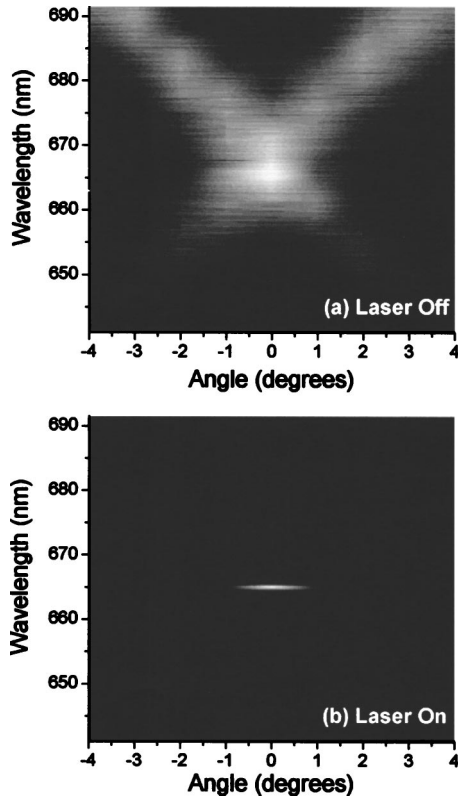


FIG. 7. Angle-dependent emission diagrams for a Dow Red F laser structure for excitation (a) below and (b) above the lasing threshold ($\lambda_{ex}=532$ nm, $\lambda_{DFB}=665$ nm).

Fig. 7(a). It can be seen that, as expected, lasing occurs normal to the waveguide plane ($\theta=0^\circ$) and that the laser emission is highly directional, falling to almost zero intensity at an angle of only 1° to the waveguide normal (limited by the resolution of our measurement).

D. Stability measurements

The stability of the red 2D-DFB lasers was examined by monitoring the evolution of their output power as a function of incident pump pulse number. For these measurements, the polymer lasers were mounted in a vacuum chamber ($\sim 10^{-4}$ mbar) to limit the influence of oxygen and water. Similar conditions can be expected to apply when the lasers are encapsulated in a suitable package.

Figure 8 shows the output decay curve for a Dow Red F laser that operated initially at $\lambda=675$ nm. During these measurements the laser was pumped at an energy per pulse that was seven times the threshold energy. The laser exhibits good stability and can emit more than 2×10^7 pulses before the output energy drops to 50% of its initial value. Similar curves were obtained for the other Dow Red F lasers operating at different wavelengths. Our results illustrate the high stability of this fluorene copolymer relative to solid-state dye lasers reported in the literature.^{33–35} This observation is encouraging for the future viability of conjugated polymer amplifiers and lasers.

An interesting feature of these decays is that in contrast to the typically observed and expected exponential decays, the Dow Red F laser decays show a richer structure with a

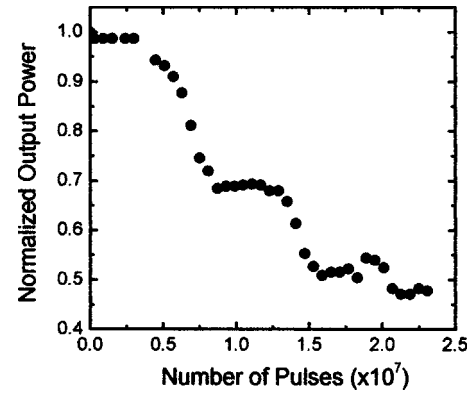


FIG. 8. Normalized laser output power as a function of incident pump pulse number ($\lambda_{ex}=532$ nm, $\lambda_{DFB}=675$ nm).

sequence of steplike features. There are then a number of plateaus across which the lasers exhibit very stable output, followed by fast drops in emission intensity. This behavior was investigated in more detail by monitoring how the properties of the laser mode changed during the lifetime measurements. In brief, it was found that the mode blueshifted by a total of ~ 0.3 nm during the set of measurements shown in Fig. 8 and that each plateau corresponded to a slightly different emission wavelength. A gradual spectral broadening of the output pulses (≤ 0.5 nm) was also observed after a large number of pulses ($> 10^5$). The spectral drifting of the laser mode can be explained by a gradual change in the effective refractive index of the guides induced by changes in morphology and/or damage of the polymer material. A small change in the refractive index of Dow Red F would then slightly shift the resonant position to a different wavelength [see Eq. (1)]. The blueshift of the laser emission is in agreement with a degradation-induced reduction of the polymer conjugation length. The observed output spectral broadening points in the same direction, as it could be attributed to broadened TE_0 mode oscillation supported by the presence of different polymer species with varying conjugation length. It should be noted that while each of these arguments could be assigned as a plausible reason for the observed phenomena, they do not provide an explanation for the quantized (discrete) character of the changes in the laser mode: What is special about the laser oscillation at each plateau region? Further studies are needed to understand the nature of degradation in these devices and identify the mechanisms that are involved.

IV. CONCLUSIONS

In summary, we have reported a detailed investigation of the lasing characteristics of in-plane two-dimensional distributed feedback structures based on the Dow Red F fluorene copolymer. The devices exhibit efficient, low threshold operation in the red spectral region, have long operating lifetimes of more than 2×10^7 pulses, and emit highly directional, azimuthally polarized output beams as a result of the 2D nature of the feedback supported by the employed laser cavities. Taking advantage of the broad gain spectrum offered by the investigated material, we have successfully fabricated lasers in which the emission wavelength could be

adjusted to lie within a very wide ($\Delta\lambda \geq 75$ nm) spectral range in the red. Using a simple waveguide DFB laser model, we showed that the experimental results are in very good agreement with theoretical predictions, demonstrating that the emission properties of these devices can be systematically controlled and modified.

Our results highlight the strong broadband gain that is accessible with polyfluorene materials and confirm the potential of conjugated polymers, in general, for the fabrication of widely tuneable solid-state lasers. Our broadband red lasers might find application in future polymer-based low cost optical communication systems. Their operating wavelengths are compatible with the maturing polymer optical fiber technology, currently under intense investigation for use in short-haul, high-speed data links.

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