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Stimulated emission and lasing in solid films of conjugated polymers: ultrafast photophysics and photon confinement via scattering

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Two major hurdles to producing solid-state polymer laser diodes are identified: the presence of a photoinduced absorption (PA) which inhibits the stimulated emission (SE) necessary for lasing; and the difficulty with making emitted light in an excited polymer travel farther than the gain length. The first of these difficulties is addressed utilizing femtosecond spectroscopic experiments on a new conjugated polymer, poly(2-butyl-5-(2′-ethyl-hexyl)-1,4-phenylene vinylene) (BuEH-PPV). The 60 ps SE decay time of BuEH-PPV is nearly an order of magnitude longer than that of other conjugated polymers, and is limited only by a dynamic blue-shift of the PA. Long SE times in polymer films open the possibility for addressing the second difficulty by producing lasing using multiple scattering. Above a critical excitation threshold, addition of TiO_2 nanoparticles to solutions and dilute blend films of poly(2-methoxy,5-(2′-ethyl-hexyloxy)1,4-phenylene-vinylene) (MEH-PPV) confines the emitted photons in the excited film until gain exceeds loss. With this technique, lasing is observed in a solid-state polymer for the first time. The combination of new materials with persistent SE like BuEH-PPV and lasing by photon confinement should open major new avenues in the production of polymer laser diodes.

1. Introduction: conjugated polymer lasers

The photophysics of conjugated polymers is of current interest because of the potential of these materials for applications in electroluminescent devices. The high density of chromophores in films of these materials results in a particularly strong ground state absorption, with typical absorption lengths of only a few hundred angstroms. Many conjugated polymers exhibit relatively high photoluminescence (PL) efficiencies with emission that is shifted sufficiently far from the absorption edge so that self-absorption is minimal (e.g. cf. figures 1 and 3). Thus, stimulated emission (SE) in these materials, which is essential to the development of lasers, is expected throughout the lifetime of the excited state. To first order, the cross-section for SE is the

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same as that for absorption, so the gain length in conjugated polymers should be essentially the same as the absorption length scaled by the fraction of chromophores in the excited state. This possibility for very short gain lengths makes these materials uniquely suited for the potential production of solid-state lasers.

The achievement of polymer laser diodes is an important goal for polymer opto-electronic devices. By utilizing SE, the quantum efficiency of luminescence can be dramatically increased, leading to highly efficient light emitting devices. The applications for bright, spectrally narrow diodes are numerous and the ease of polymer processing should offer significant advantages over inorganic materials. Despite these potential advantages, laser action from a conjugated polymer in the solid state has yet to be achieved. There are two problems facing the production of polymer lasers: photophysics and gain extraction. The photophysical difficulty lies in the presence of photoinduced absorption (PA) which often occurs in the same spectral region as the emission. Since the PA has a comparable cross-section to the SE, competition between the two effectively inhibits gain. The difficulty with gain extraction is that, even in the presence of SE, the emitted photons must travel a distance through excited polymer longer than the gain length for lasing to occur. Although high-Q etalons have been constructed around conjugated polymer films to achieve longer path lengths, to date, the gain has not exceeded the losses in any of these microcavity structures.

In this article, we summarize initial progress toward the development of polymer laser diodes by attacking the two problems discussed in the previous paragraph. The first approach, outlined in §2, utilizes femtosecond spectroscopy to explore the elementary photophysics of conjugated polymers (Schwartz *et al.* 1997). Examination of different conjugated polymers suggests that the spectral position of the PA can be partially controlled via choice of side group. Using a newly synthesized alkyl-substituted conjugated polymer, we demonstrate stimulated emission which persists for over 60 ps, nearly an order of magnitude longer than in other semiconducting polymers. Next, in §3, we describe how the introduction of titanium dioxide nanoparticles can lead to efficient gain extraction by multiple scattering (Hide *et al.* 1996). With the appropriate concentration of titania particles, emitted photons cannot leave the sample until after they have traveled a distance greater than the gain length due to confinement by multiple scattering. With this technique, we demonstrate optically pumped lasing of conjugated polymers in solid films for the first time. Finally, in §4, we summarize the potential for producing electrically pumped solid-state polymer laser diodes by combining these two approaches.

2. Controlling stimulated emission in conjugated polymers

Ultrafast spectroscopic studies of various conjugated polymers have revealed that, although SE is readily observed in solutions and dilute blend films, in neat solid films SE is either not observed or decays within at most a few ps (Yan *et al.* 1994*a, b*, 1995; Graupner *et al.* 1996; Pauk *et al.* 1995). The absence of SE results from a strong PA which overwhelms the SE in neat films, but not when the polymer chains are isolated in solution or in dilute blends. The exact nature of this sub-gap PA has been a subject of debate (Hsu *et al.* 1994); however, it seems clear that the bulk of PA in solid films must be due to an interchain electronic species. Whatever the origin of the PA, the absence of observable SE implies that the excited medium does not exhibit gain, indicating that polymer lasers and solid-state polymer laser diodes are not possible.
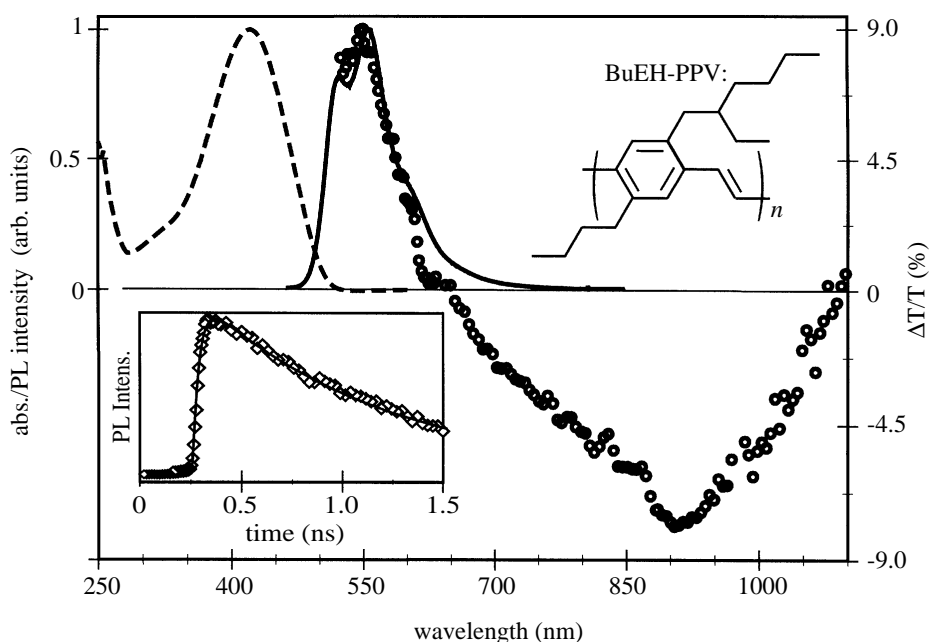
Figure 1. Fractional change in probe transmission ($\Delta T/T$) versus photon energy at 'zero' time delay for BuEH-PPV films (open circles, right axis). For reference, the steady-state PL (solid curve, arbitrary units) and absorption (dashed curve, arbitrary units) are also shown. Upper inset: chemical structure of BuEH-PPV. Lower inset: spectrally integrated PL decay of BuEH-PPV excited at 440 nm recorded on a streak camera (diamonds) and exponential fit (solid curve).

In this section, we present the results of femtosecond spectroscopic studies on a new semiconducting polymer, poly(2-butyl-5-(2′-ethyl-hexyl)-1,4-phenylenevinylene) (BuEH-PPV). The presence of the bulky alkyl substituents produces a enough of a red-shift of the PA to significantly reduce spectral overlap with the emission. We find that SE in neat solid films of BuEH-PPV at room temperature persists for over 60 ps and show that the discrepancy between the *ca.* 60 ps SE decay time and the *ca.* 900 ps decay of the PL results from a dynamic blue-shift of the PA which causes the PA to mask the SE at longer times.

Femtosecond pump-probe experiments were performed using the second harmonic of an amplified CPM laser (310 nm, *ca.* 100 fs, 0.3 µJ, 1 kHz) to excite the sample and a mechanically delayed white-light continuum generated from the remaining fundamental light to probe the spectral dynamics. Spectral signals recorded on a CCD array were double-normalized utilizing signal and reference probe beams both with and without the pump light, as described previously (Schwartz *et al.* 1997). The magnitudes of the PA and SE signals at zero time delay (*ca.* 10% $\Delta T/T$) were linear with pump intensity. The relative polarization of the pump and probe light was set to the magic angle. Films of BuEH-PPV, synthesized as described elsewhere (Andersson *et al.* 1997), were drop-cast from *o*-dichlorobenzene with *ca.* 1 µm thickness on sapphire substrates in a N_2 atmosphere (glass substrates led to problems with sample heating under fs UV excitation). The samples were placed immediately in an optical cryostat at room temperature and kept under dynamic vacuum (*ca.* 2 mTorr) during the experiments.

Figure 1 presents the ground state absorption (dashed curve), PL (solid curve)
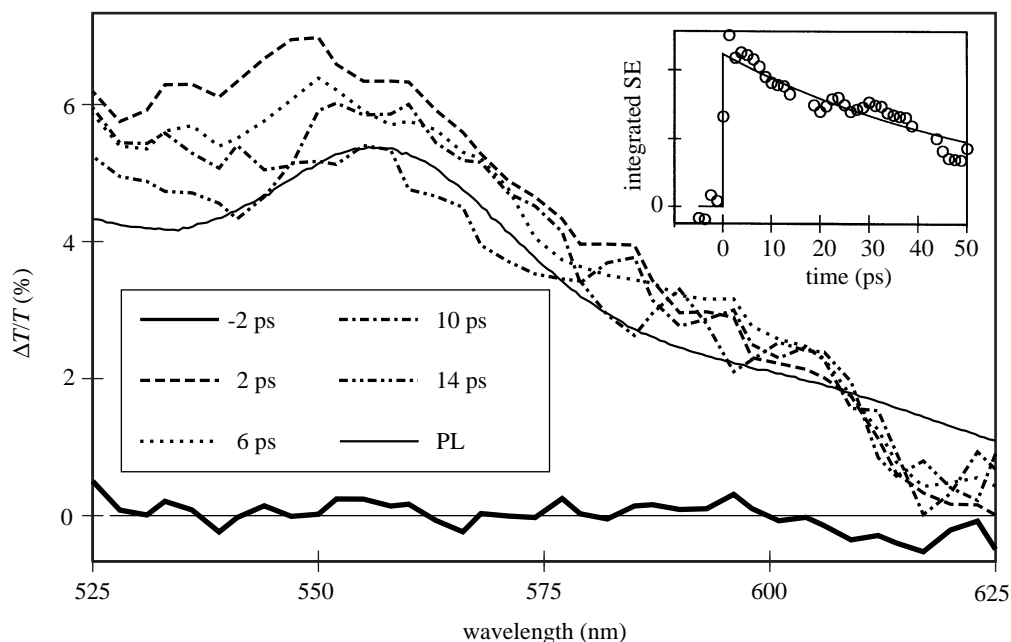
Figure 2. Early time SE dynamics of BuEH-PPV at 2 ps (dashed curve), 6 ps (dotted curve), 10 ps (dot-dashed curve) and 14 ps (dot-dot-dashed curve) following 310 nm photoexcitation. The spectrum before excitation (-2 ps, thick solid curve) and the steady-state PL (thin solid curve, arbitrary units) are shown for reference. Inset: 525–575 nm spectrally integrated decay of the SE.

and molecular structure of BuEH-PPV. This material is highly luminescent; the PL quantum yield for 430 nm excitation is 0.62 in films and 0.75 in tetrahydrofuran solutions (Andersson *et al.* 1997). The inset in figure 1 shows the time dependence of the spectrally integrated PL; the thin solid line is a fit to the streak camera instrument rise and a single exponential decay with a time constant of 914 ps. The high PL quantum yield and correspondingly long PL decay time compared to other substituted PPVs is likely the result of reduced interchain interactions caused by the presence of the bulky alkyl side-chains (Staring *et al.* 1994).

The gain spectrum and transient absorption of BuEH-PPV immediately following photoexcitation are displayed as the open circles in figure 1. In the 520–620 nm region, the probe undergoes an increase in transmission, corresponding to strong SE gain, a feature not commonly observed in the transient spectroscopy of other conjugated polymer films. The early time SE closely resembles the equilibrium PL spectrum, indicating that the emissive species is formed exceedingly rapidly. To the red of 620 nm, the nascent excited state spectrum consists of a broad PA extending well into the near IR. Although qualitatively similar to that observed in other conjugated polymers (Yan *et al.* 1994*a, b*, 1995; Graupner *et al.* 1996; Pauck *et al.* 1995), the PA is broader and is red shifted in BuEH-PPV. This difference is also likely related to the decreased interchain interactions in BuEH-PPV compared to other substituted PPVs.

Careful inspection indicates that the nascent SE gain is blue-shifted from the steady-state PL. Figure 2 displays the early time spectral dynamics of the SE; the SE undergoes a red shift over the first *ca.* 15 ps following photoexcitation. Although

similar dynamic Stokes shifts, where the transient PL takes a similar time to evolve into the steady-state PL, have been observed in other semiconducting polymers (Kersting *et al.* 1993; Hayes *et al.* 1995), this is the first observation of this phenomena in a polymer via SE. The previous discussions of the transient PL have assigned this dynamic red shift to energy transfer through an inhomogeneous density of states.

The inset in figure 2 displays the time evolution of the SE, spectrally integrated from 525–575 nm. The solid curve is a single exponential fit to the data with a decay time of 60 ps. This represents the longest SE decay time observed in a conjugated polymer by nearly an order of magnitude. Measurements of the short-lived SE in PPV showed that the SE decay time decreased as the pump energy was increased above the band edge and that the SE completely vanished for sufficiently blue excitation (Yan *et al.* 1994*a, b*). For the BuEH-PPV experiments reported here, the 4.0 eV photon energy of the pump light is nearly 1.5 eV larger than the band gap. Thus, if BuEH-PPV behaves in a similar fashion to PPV as expected from their similar electronic structures, the SE decay time should be considerably longer than 60 ps for near band edge excitation.

Basic radiation theory predicts that the time decay of the SE and PL should be the same and equal to the lifetime of the excited state (Yariv 1989). Why, then, does the SE in BuEH-PPV (although relatively long lived compared to other conjugated polymers) decay so much more quickly than the PL? Since the excited states that produce the PL live for 900 ps, the more rapid SE decay must result from a masking PA in the emissive region which appears on the 60 ps time scale. This PA could result either from an excited species which takes 60 ps to form or from a dynamic blue-shift of the near IR PA which takes 60 ps to completely mask the SE. Understanding the interaction between the PA and SE is the key to controlling the gain of the medium and to eventually producing lasers from solid conjugated polymers.

Investigation of the near-IR PA decay dynamics shows evidence for a clear blue-shift; on the *ca.* 100 ps time scale, the PA decays more quickly in the red than the blue (Schwartz *et al.* 1997). This is likely the result of large scale structural relaxation, bringing the chains on which the interchain species reside closer together until their configuration more closely resembles that of other substituted PPV derivatives where the PA overlaps the SE completely from time zero. This blue-shift of the PA leads to the 60 ps decay of the SE (figure 2). This observation provides a prescription for synthesizing new conjugated polymers even with longer-lived SE; the interchain structure must start with the proper chain separation and orientation such that the interchain PA does not overlap the SE. Moreover, the structure should be made sufficiently rigid (e.g. by using bulky, rigid side-groups or via cross-linking) so that structural relaxation around the interchain excitation does not subsequently mask the SE.

3. Polymer lasers by scattering from TiO$_2$ nanoparticles

With our improved understanding of the requirements for achieving SE in conjugated polymers, we turn to the issue of actually constructing a polymer laser. As mentioned in the introduction, the traditional approach for controlling the emission from conjugated polymers centers on microcavities which require construction of high-Q resonant cavities for each polymer or desired wavelength (Wittmann *et al.* 1995; Lemmer *et al.* 1995; Fisher *et al.* 1995). These microcavities restrict the allowed modes of the radiation field, redistributing emission by increasing the emission in-
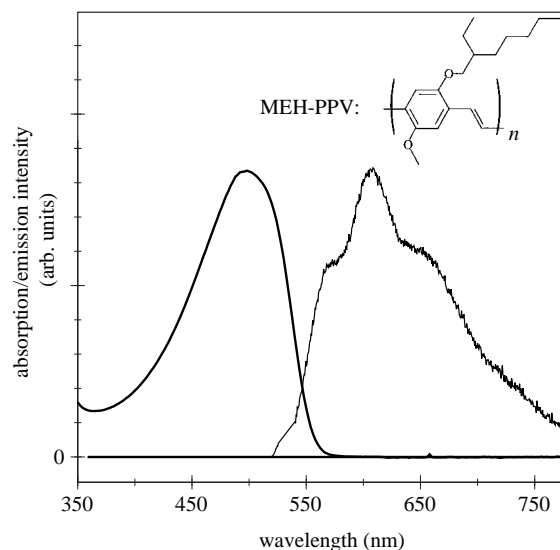
Figure 3. Absorption (heavy smooth curve) and PL (thin, slightly noisy curve) spectra of dilute solutions of MEH-PPV in cyclohexanone in a 1 mm cuvette. The absorption was measured with a 0.01% w/v solution and the PL measurements were performed with low energy 532 nm excitation in a 0.1% w/v solution. Inset: chemical structure of MEH-PPV.

tensity at some wavelengths at the expense of others. However, construction of these etalons negates the advantages offered by polymers in ease of processing.

In this section, we report an alternate approach for producing lasing in solutions and solid films of conjugated polymers. Our procedure exploits the recent work of Lawandy *et al.* (1994), who demonstrated isotropic laser emission from optically pumped dye solutions containing colloidally suspended titanium dioxide (TiO_2) particles. The idea underlying this approach is straightforward. Scattering off the randomly distributed high-index of refraction titania nanoparticles greatly increases the path length traversed by the emitted light. This allows stimulated emission gain to occur if the medium is pumped above threshold and the scattering length exceeds the gain length. In essence, the colloidal particles function as an isotropic, random microcavity which provides the feedback necessary for laser action (Wiersma *et al.* 1995; Genack & Drake 1994; Noginov *et al.* 1995). Here, we achieve lasing action with this method for both solutions and dilute blend films of poly(2-methoxy,5-(2′-ethyl-hexyloxy)1,4-phenylene-vinylene) (MEH-PPV, see figure 3). This represents the first demonstration of lasing with a conjugated polymer in the solid state as the active medium (Hide *et al.* 1996).

The key requirement to demonstrating lasing from conjugated polymers is finding a system that exhibits SE. Since the experiments described in this section were done concurrently with the femtosecond studies described in the previous section, we did not choose BuEH-PPV for our initial studies in this area. Instead, we selected MEH-PPV, which offers several advantages in terms of its solubility in conjugated form in common organic solvents and the relatively high brightness and efficiency of light-emitting diodes (LEDs) (Gustafsson *et al.* 1992) and light-emitting electrochemical cells (LECs) (Pei *et al.* 1995, 1996; Bard 1995) made from this material. Ultrafast spectroscopy showed stimulated emission from MEH-PPV in solutions and in dilute host polymer films (Yan *et al.* 1995), a result consistent with reports of photopumped

lasing in concentrated MEH-PPV solutions (Moses 1992). These femtosecond studies indicate, however, that stimulated emission in pure MEH-PPV is inhibited in the solid state, presumably due to interchain interactions (Yan *et al.* 1995). Thus, gain narrowing by scattering from titania particles is expected with MEH-PPV only in solutions and in dilute solid films.

MEH-PPV was obtained from UNIAX Corporation and used as received. Solutions of MEH-PPV and the desired amount of titania particles in cyclohexanone were prepared by stirring at room temperature in a nitrogen environment. The titania particles were obtained from DuPont Chemicals (Ti-Pure R900) and had an average diameter of 270 nm. For luminescence measurements, the solutions were transferred to 1 mm sealed glass cuvettes. Dilute solid films of MEH-PPV were prepared using polystyrene (PS) (MW $125\,000 \sim 250\,000$, from Polysciences, Inc.) as the inert matrix. Films were cast from a solution containing 0.5 g of PS and the desired amount of chemically silated titania particles and MEH-PPV, all in tetrahydrofuran (THF). Concentrated solutions of PS (20% w/v) were used, making the mixture sufficiently viscous to prevent sedimentation of the titania particles during processing. The mixture was spread in a small Petri dish and dried at $35\,^{\circ}$C, yielding homogeneous free-standing films with typical thicknesses of $150 \sim 250\,\mu$m.

PL experiments were performed at room temperature following Lawandy *et al.* (1994). The frequency doubled output (532 nm) of a 10 Hz, Q-switched Nd:YAG laser (Spectra Physics Quanta-Ray DCR-3) served as the excitation source. The *ca.* ns pulses, focused to a spot size of *ca.* 1.5 mm, were incident on the samples at a 30° angle to avoid the possibility of lasing off the cell walls or film edges. The emission that passed through a *ca.* 2 mm aperture placed normal to the front face of the sample was collected, frequency dispersed in a single monochromator (Spex), and detected by a Peltier-cooled CCD array (Photometrics). A typical experimental run recorded changes in the PL spectrum as a function of the excitation energy per pulse. The geometry we employed enabled us to reproduce the emission results of Lawandy *et al.* (1994) on TiO_2 particles suspended in Rhodamine 640/methanol solutions.

Initial experiments examined the effects of titania particles on the PL of MEH-PPV in solution (0.6% w/v in cyclohexanone). The PL spectrum (see figure 3), characterized by a vibronic series with the 0-0 transition at ≈ 570 nm, remains essentially constant with increasing pump energy, as indicated by the solid curve in figure 4a. In the presence of *ca.* 10^{10} cm^{-3} titania particles, however, dramatic gain narrowing is observed (figure 4a, dashed curve) when pumped above the threshold for stimulated emission, indicative of laser action.

The effect of pump energy on the PL of MEH-PPV:TiO_2 solutions is presented in figure 4b, which shows the spectra obtained from a 1.0% w/v solution of MEH-PPV in cyclohexanone with *ca.* 10^{11} cm^{-3} suspended TiO_2 nanocrystals pumped at two energies: 0.12 mJ (solid curve) and 3.6 mJ (dashed curve). The solid curve is the typical broad emission from MEH-PPV. The dashed curve shows emission from the same solution pumped well above the lasing threshold. Again, striking gain narrowing is observed, as well as a blue-shift of the narrowed emission with respect to the low-energy luminescence (cf. figure 5b below). The high energy vibronic shoulder, corresponding to the 0-0 transition observed at lower MEH-PPV concentrations (figure 3), is suppressed in this concentrated solution. The amplitude of this feature decreases with increasing MEH-PPV or particle concentrations, consistent with self-absorption.

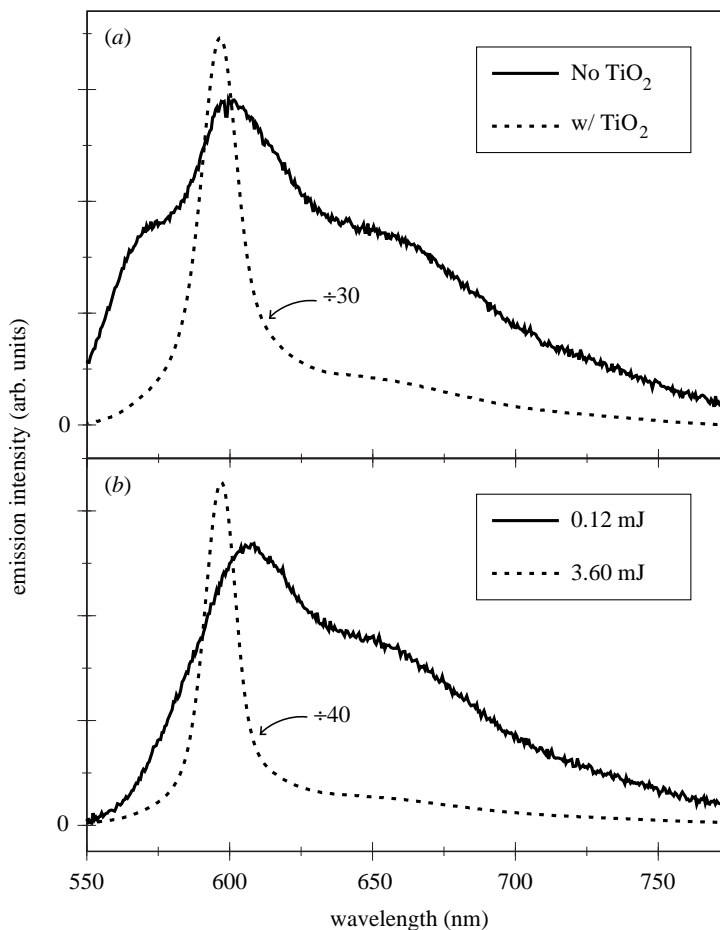Figure 5a displays the dependence of the emission line width as a function of

Figure 4. (a) Effect of TiO$_2$ nanoparticles on the luminescence of MEH-PPV/cyclohexanone solutions: solid curve—PL of 0.6% w/v MEH-PPV solution pumped with 4.5 mJ of 532 nm light; dashed curve—PL of the same solution under identical excitation conditions after addition of ca. 10^{10} cm^{-3} titania particles. (b) Effect of excitation energy on the luminescence of MEH-PPV/cyclohexanone solution (1.0% w/v) with ca. 10^{11} cm^{-3} titania particles.

pump energy for the solution of figure 4a (0.6% w/v MEH-PPV in cyclohexanone, ca. 10^{10} cm^{-3} titania particles). We have chosen the full width at $1/e$ height to represent the line width of the emission spectra since this is more suitable (compared to other definitions such as FWHM) for comparison of disparate emission spectra with varying magnitudes of vibronic features. The solid squares show a factor of about five decrease in line width and indicate that the threshold for laser action occurs at ca. 1 mJ. The open circles represent the line width for an identical MEH-PPV solution without titania particles. Clearly, the scattering particles are crucial to the achievement of gain narrowing in these solutions. The MEH-PPV solution results (figures 4 and 5a) are in good qualitative agreement with those obtained earlier from dye solutions (Lawandy et al. 1994; Sha et al. 1994; Zhang et al. 1995; Noginov et al. 1995).

One interesting feature of the scattering polymer solutions not observed in dye solutions is a definite blue-shift of the emitted light with increasing excitation energy.
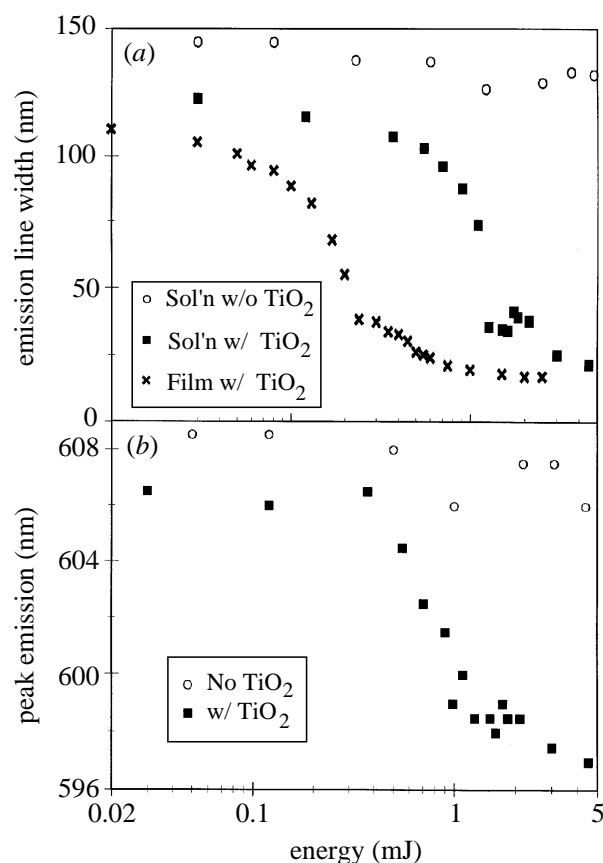
Figure 5. (*a*) Emission line width (full width at $1/e$ height) as a function of energy for scattering MEH-PPV/cyclohexanone solutions and PS dilute blend films: open circles—0.6% w/v MEH-PPV solution with no titania particles (same as solid curve in figure 2*a*); solid squares—identical solution after addition of *ca.* 10^{10} cm^{-3} TiO$_2$ nanocrystals (same as dashed curve in figure 4*a*); crosses—0.9% w/w MEH-PPV in PS free-standing film with *ca.* 10^{11} cm^{-3} titania particles; cf. figure 6. (*b*) Emission peak position as a function of energy for the same MEH-PPV and MEH-PPV:TiO$_2$ solutions.

Figure 5*b* presents the wavelength of the emission maximum as a function of pump energy for the same solution used for obtaining the data in figure 4*a* and figure 5*a* (solid squares). The emission peak blue-shifts precipitously at approximately the same energy as the collapse of the emission line width, providing further evidence of laser action. We believe that this blue-shift is a result of temporal narrowing of the emitted laser light. Ultrafast PL measurements of MEH-PPV (Hayes *et al.* 1995) show an initially blue-shifted PL spectrum which evolves to the steady-state emission spectrum over the first tens of ps following photoexcitation, similar to that observed in the previous section by SE in BuEH-PPV. Streak camera measurements indicate that the gain-narrowed emission in scattering dye solutions also occurs on the tens of ps time scale (Sha *et al.* 1994). Thus, above the lasing threshold, stimulated emission in scattering polymer solutions largely occurs before energy transfer can take place, resulting in enhanced gain from the early time blue-shifted emission. Since the gain-narrowed emission provides a PL 'window' backwards in time, the observation of
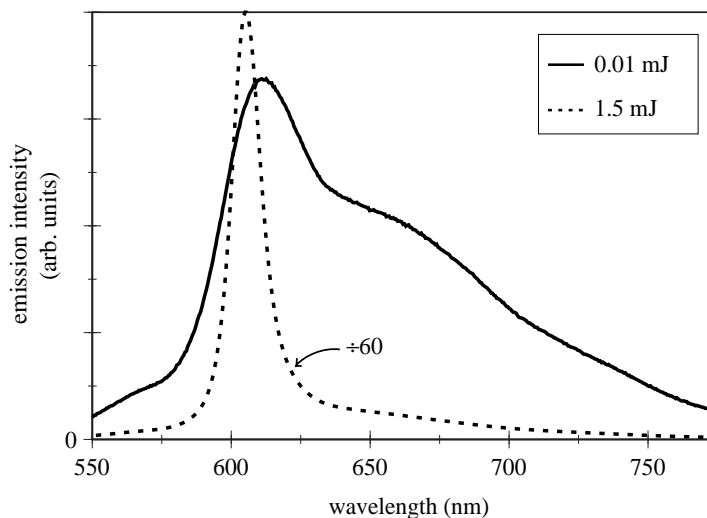
Figure 6. Effect of excitation energy on the luminescence of dilute free-standing films of MEH-PPV (0.9% w/w) in PS with *ca.* 10^{11} cm^{-3} titania particles.

gain-narrowing can serve as a litmus test for the presence of SE in given conjugated polymer without the need for costly femtosecond pump-probe experiments such as those described in the previous section.

The observation of laser action in solutions provides insight for the achievement of lasing in solid polymer films (Balachandran *et al.* 1996; Hide *et al.* 1996). The emission spectra from a dilute (0.9% w/w) blend of MEH-PPV in PS with *ca.* 10^{11} cm^{-3} titania nanoparticles above and below the lasing threshold are shown in figure 6. Clearly, gain narrowing occurs in the solid film; the final line width is slightly narrower and the long wavelength luminescence tail is better suppressed in the film than in the comparably concentrated solution. The gain narrowing as a function of energy for this film is shown as the crosses in figure 5a. The collapse of the line width and the blue-shift of the emission peak for the solid polymer film occur at nearly an order of magnitude lower energy than in the comparably concentrated solution. This is likely the result of the higher density of chromophores available in the solid films compared to solution.

The observation of polymer lasing in the solid state is encouraging in another respect; laser action occurs at energies well below the onset of optical damage. For all films, there is an energy threshold above which dark spots appear, accompanied by an increase in the emission line width. In our standard geometry, the damage threshold occurs near 2.5 mJ, nearly an order of magnitude higher in energy than the threshold for gain narrowing. As expected, both the lasing and damage thresholds are sensitive to the excitation spot size.

4. Future directions for conjugated polymer lasers

Efforts are presently underway to investigate the feasibility of making an electrically pumped solid-state laser with a semiconducting polymer as the active gain medium. Our approach of using scattering to produce lasing has several advantages. Lasing action provides an increase in the luminescence quantum yield, offering the

possibility for more efficient EL devices. The isotropic nature of the scattered laser light should fit well with the requirements of many applications. Titania nanoparticles are inexpensive and readily available in industrial quantities. Moreover, TiO_2 can be incorporated into existing polymer processing technologies with minimal disruption. Finally, TiO_2 scatters uniformly over the entire visible spectrum, making this approach applicable to conducting polymers that emit in any spectral region.

Despite these advantages, realization of solid-state polymer laser diodes will require progress in achieving current densities sufficient to surpass the laser threshold by electrical pumping. At present, current densities of $25\,\mathrm{A\,cm^{-2}}$ have been reported in electrically pulsed MEH-PPV diodes ($4 \times 10^{-3}\,\mathrm{cm^2}$ area) when operated with $3\,\mu\mathrm{s}$ pulses at a low duty cycle (Braun *et al.* 1992). With

improved thermal management, smaller active areas and shorter current pulses, significantly higher current densities should be possible. Based on the photon densities used in the above study and assuming a *ca.* 1% quantum efficiency for electroluminescence, the transient current densities necessary to reach the threshold for gain narrowing will likely be *ca.* $10^5\,\mathrm{A\,cm^{-2}}$. However, conjugated polymers like BuEH-PPV, which show SE in neat films, will have a much higher density of chromophores than the dilute MEH-PPV/PS blends discussed above and thus will likely have significantly lower thresholds for gain narrowing. Moreover, neat films will provide much better charge transport than dilute blends of conjugated polymers in inert host matrices. Thus, the combination of new polymers which exhibit persistent SE and photon confinement by scattering offer real potential for the development of solid-state polymer laser diodes.

In summary, we have used scattering from titanium dioxide nanocrystals to produce laser action from optically pumped solutions and free-standing dilute blend films of the conducting polymer MEH-PPV. Gain narrowing was observed above a critical pump threshold for several polymer and particle concentrations. The polymer emission exhibits a blue shift at approximately the same threshold pump energy. We believe this constitutes the first observation of lasing from a conjugated polymer in the solid state. We also have measured the transient absorption and emission dynamics of a new conjugated polymer, BuEH-PPV. Unlike other substituted PPVs, room temperature films of BuEH-PPV show strong SE, even when pumped significantly above the band gap. Even though the PL of BuEH-PPV takes *ca.* 900 ps to decay, the SE decays in *ca.* 60 ps because of a dynamic blue-shift of the PA on this time scale. This relatively long SE time has important implications for the construction of polymer lasers; since the SE time in scattering media is usually on the order of tens of ps, a polymer like BuEH-PPV could be incorporated directly into a scattering polymer laser diode without the need for dilution.

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