

# A Kerr Mode-Locked Semiconductor Laser: Design and Theory

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**Abstract**—We propose a novel type of semiconductor laser mode-locked by the Kerr-effect induced refractive index change of a polymer. Such a device is shown to have the potential to produce dramatically shorter pulses than those devices currently in use.

**Index Terms**—Mode locked lasers, nonlinear optics, optical Kerr effect, optical polymers, optical pulse generation, photonic crystal, semiconductor lasers.

## I. INTRODUCTION

IN RECENT years, much time and effort has been spent in the search for a monolithic femtosecond diode laser. Such a device has many applications, particularly as a source for wavelength division multiplexing (WDM) in optical telecommunications. It would have the advantage of being electrically pumped, compact, and mechanically stable. Currently available devices typically produce pulses of 1–2 ps duration [1], although 200 fs pulses have been produced using an external cavity and external compression [2]. This underlines the inherent potential of semiconductor lasers for producing femtosecond pulses.

In this paper, we propose a design for a monolithic semiconductor laser that is mode-locked by the Kerr effect. Such a laser would have many advantages over standard semiconductor lasers mode-locked using a saturable absorber especially a much improved ability to produce short pulses. The pulsewidth produced by a laser is determined by the interplay between the pulse shortening mechanism and pulse lengthening effects due to group velocity dispersion and self-phase modulation (SPM) [3]. In standard semiconductor lasers, the pulse shortening rate is limited by the recovery time of the saturable absorber, which is of the order of 5–50 ps when the recovery mechanism is an applied reverse bias [4] and 2 ps in the case of saturable absorption by ion implantation [5]. However, the Kerr effect, by its electronic nature, is instantaneous, potentially offering much stronger mode-locking. This has already been used to great effect in Ti:Sapphire lasers in the form of Kerr-lens mode-locking [6].

The introduction of colliding pulse mode-locking (CPM) [which has a stronger mode-locking effect than a simple two-section device due to the higher pulse intensity in the saturable absorber] has resulted in the shortest pulses to date from a monolithic diode laser, as generally, for a given amount of cavity dispersion, stronger mode-locking produces a shorter pulse. Wu *et al.* have demonstrated 1.4-ps pulses from a CPM diode [1] and Martins-Filho *et al.* 1.3-ps pulses using multiple

colliding pulse mode-locking [7]. Yanson *et al.* have extended this idea to high harmonic mode-locking, demonstrating subpicosecond pulses at very high repetition rates [8]. However, the extremely high repetition rate and corresponding low peak powers limit the usefulness of this approach.

When using an external cavity system, intracavity chirp compensation may be introduced reducing the amount of pulse lengthening that must be overcome [9]. As the pulse circulating in the cavity gets shorter however, the effects of carrier heating and other effects such as gain dispersion become important, resulting in highly nonlinear chirping. For example, the breakup of a 650-fs pulse propagating in a semiconductor optical amplifier (SOA) has been observed [11]. This indicates that the monolithic production of pulses shorter than 600–700 fs will be difficult. Azouz *et al.* suggest that keeping the pulse relatively long (with a corresponding low peak intensity) in the gain medium offers advantages as this prevents intensity induced nonlinear effects. An external compressor can then be used to compress the relatively simply chirped pulses [12].

The use of a quantum dot gain medium for a mode-locked laser offers some advantages. Quantum dots have been shown to have a very small line-width enhancement factor compared to quantum wells [13]. The effects of the nonlinear gain dynamics are complicated [14], suggesting that this will limit the pulse duration as such devices still rely on a waveguide saturable absorber for the mode-locking method.

Tropper *et al.* have demonstrated subpicosecond pulses in an external cavity surface emitting system [15]. This system uses the AC Stark effect in a semiconductor saturable absorber mirror (SESAM) to provide a strong form of mode-locking giving the capability to produce transform-limited 620 fs pulses (shorter pulses were also produced but were not transform limited). This system, as a result of its surfacing-emitting nature, avoids most of the large self-phase modulation inherent in stripe-geometry lasers, but it does indicate the possibility of overcoming chirping due to carrier heating (at least for pulses greater than 500 fs). A SESAM typically has a stronger mode-locking effect than a simple intracavity saturable absorber [16], thus allowing the effects of nonlinear gain dynamics to be at least partially overcome.

Thus, increasing the mode-locking strength seems to be one of the most promising options in the quest for shorter pulses.

## II. DESIGN

In Kerr-lens mode-locked lasers, the self-focusing effect of a high-energy pulse reduces the loss experienced on reflection from a mirror, mode-locking the laser. We seek to recreate this effect by making the reflection coefficient of one of the cavity end mirrors intensity-dependent. Our modeling shows that it

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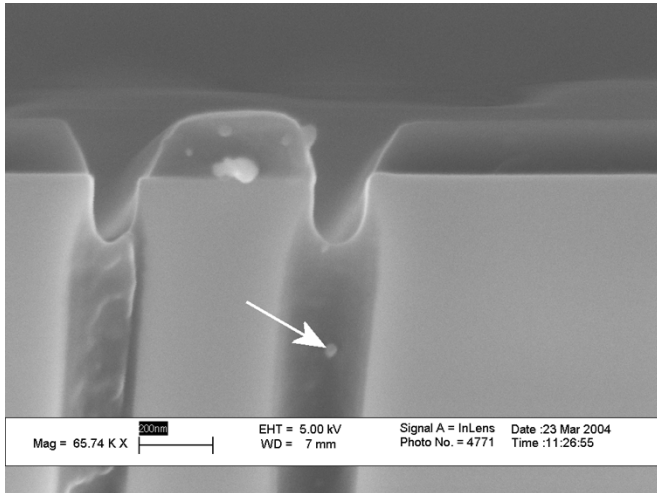


Fig. 1. Scanning electron microscope image of a polymer filled photonic crystal. A contamination spot (marked) has been burnt confirming that the polymer fills the feature.

takes a reflectivity increase of approximately 25% to start mode-locking, though only 1%–2% is necessary to sustain Kerr mode-locking and shorten the pulses once pulsing has started. In order to achieve this, we intend to use a photonic bandgap mirror [17], incorporating a polymer with a large Kerr coefficient, as one of the end mirrors. The position of the bandgap is determined by the period of the mirror and by the refractive indexes of its components. Thus, when the refractive index of the polymer changes under the influence of a high power pulse, (1), the position of the bandgap shifts. The change in refractive index  $n$  induced by an optical field intensity  $I$  is given by

$$n = n_0 + n_2 I \quad (1)$$

where  $n_0$  is the linear refractive index and  $n_2$  is the Kerr coefficient.

The mirror is filled with polymer using an embossing technique. A thick layer of polymer is spun onto the sample and then pressure and heat is applied to force the polymer into the etched features, see Fig. 1. A related technique has been used to create tunable photonic crystals [18].

It might be envisaged that these mirrors may be fabricated by lithographically tuning one of the mirrors [19]. By choosing the tuning step fine enough, it should be possible to achieve the required overlap.

In order to produce the largest reflectivity change at the lasing wavelength for a given change in refractive index, it would be preferable to operate on the band edge of the mirror. To this end, we use two asymmetric Bragg mirrors to define the cavity, see Fig. 2. Their periods are chosen such that bandgap of the front (infilled with polymer) mirror is offset to longer wavelengths from the rear mirror, with an overlap occurring only between the edges, see Fig. 3. If the refractive index of the low-index sections in the front mirror decreases, then its bandgap shifts to shorter wavelengths, increasing the overlap between the two asymmetric bandgaps, see Fig. 4. There are a number of potential polymers that could be used. For example, Polycarbonate is reported to have a  $n_2$  of  $-2.99 \times 10^{-11} \text{ cm}^2 \text{ W}^{-1}$  [20]. Polydiacetylene in crystalline form has a  $n_2$  of  $3 \times 10^{-8} \text{ cm}^2 \text{ W}^{-1}$

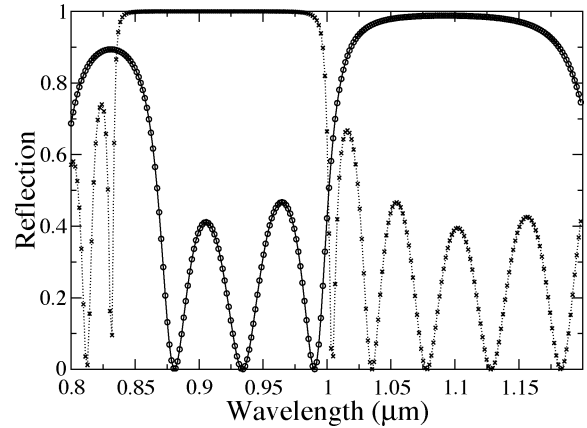
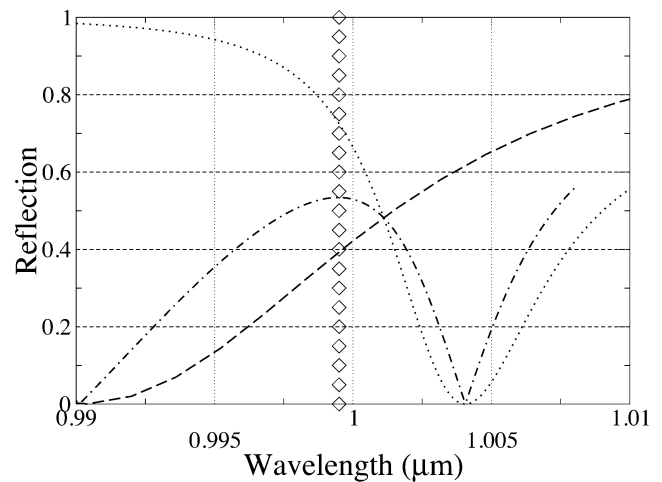
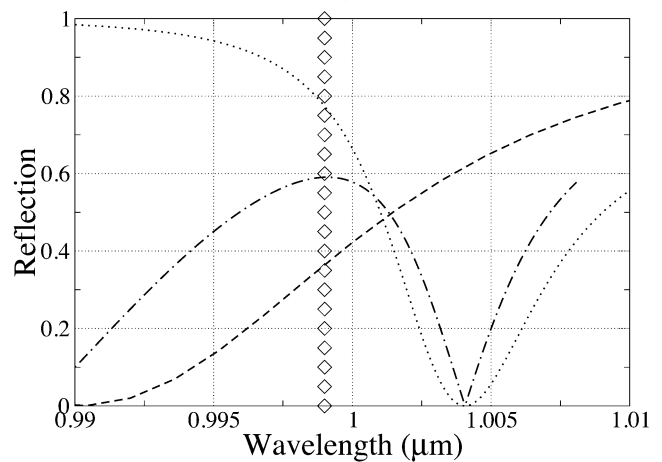


Fig. 2. Bandgaps of the two mirrors show only a small overlap at low light intensity. Crosses indicate the back mirror and circles the polymer-filled front mirror.



(a)



(b)

Fig. 3. (a) Unshifted case. (b) Under the influence of a high-energy pulse that causes a refractive index change of  $-0.005$ . The squared line corresponds to the rear unfilled mirror, the circle to the front polymer-infilled mirror and the diamonds to the total reflectance. The vertical line (diamonds) indicates the lasing wavelength.

[21]. Soluble forms exist but with a reduction in the value of  $n_2$ . Soluble polymers [dialkylaminonitrodiphenylpolyene (DANS)] with even stronger  $n_2$  values ( $7 \times 10^{-8} \text{ cm}^2 \text{ W}^{-1}$ ) are reported in [22]. The problem of photostability must be considered, since

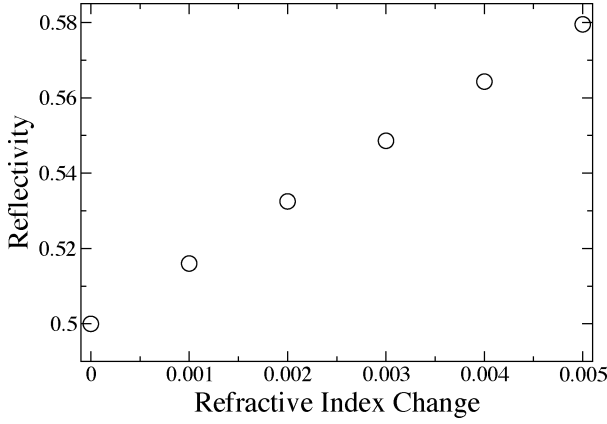


Fig. 4. Diagram showing how the total cavity reflectance changes with the polymer refractive index change.

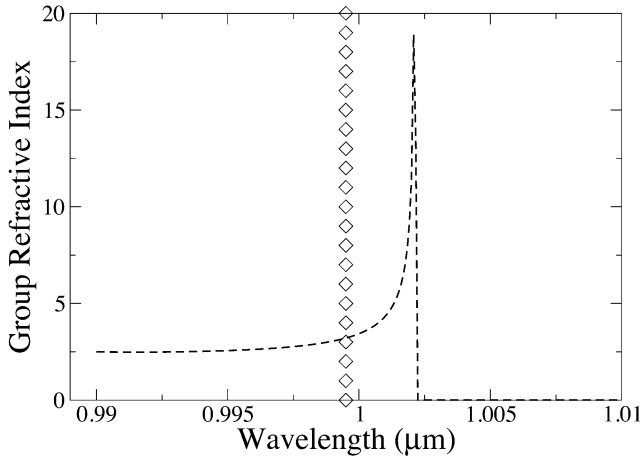


Fig. 5. This shows the dispersion of the polymer filled mirror approaching its band edge. Calculated from the group velocity following [32]. The lasing wavelength is indicated by a vertical line (diamonds).

the polymers examined in [22] have a shorter life than would be required for commercial use [23]. Polycarbonate should be more resilient, in this respect, as its peak absorption (295, 345 nm) [24], is further from the wavelengths of interest than that of DANS (approx. 500 nm), yet its  $n_2$  value is already sufficient to produce a significant improvement, as will be demonstrated in Section III-B.

The Kerr coefficient of the polymer could be enhanced in the Bragg mirror as a result of the reduction in the group velocity, see Fig. 5. Very low group velocities have been observed in one-dimensional photonic bandgap structures [26]. For the front mirror, the low-index region is chosen to be large in order to increase the interaction of the light with the polymer, also the mirror period of the polymer is chosen such that lasing takes place at the shorter wavelength edge of the bandgap. This results in the majority of the light building up in the low index regions thereby enhancing the influence of the polymer.

### III. THEORY

#### A. Modeling

The model is adapted and extended from that reported by Schell *et al.* [27]. It is described in greater detail in [28]. Our

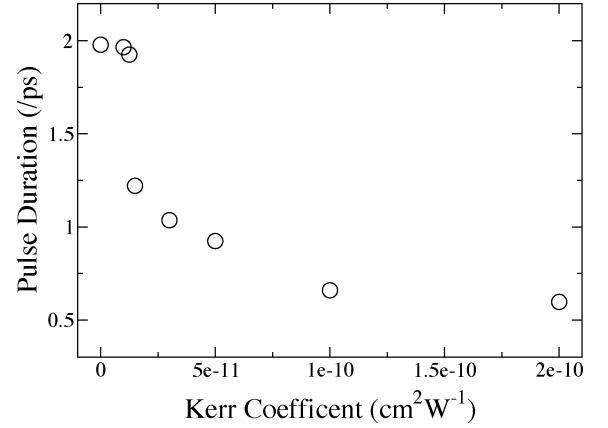


Fig. 6. Pulsewidth with respect to Kerr coefficient in the hybrid case. This clearly shows the transition between saturable absorber mode-locking and Kerr effect mode-locking. This device had a 3000  $\mu\text{m}$  gain section and a 300  $\mu\text{m}$  absorber.

time-domain model consists of a set of counter-propagating coupled traveling-wave equations representing the forward ( $E^+$ ) and backward ( $E^-$ ) traveling slowly varying complex envelopes

$$\left( \frac{\partial}{\partial t} \pm \nu_g \frac{\partial}{\partial z} \right) E^\pm = \frac{(\nu_g \Gamma g - \kappa)}{2} E^\pm(z, t). \quad (2)$$

We model the complex nonlinear gain  $g$ , following [31], and carrier concentration dynamics  $N$  with

$$g_0 = g_n \frac{(N - N_0)(1 + i\alpha)}{1 + \epsilon S} \quad (3)$$

$$\frac{\partial g}{\partial t} = \frac{g_0 - g}{t_{nl}} \quad (4)$$

$$\frac{\partial N}{\partial t} = \frac{J}{ed} - \frac{N}{\tau_n} + BN^2 + CN^3 - \nu_g \Re(g)S \quad (5)$$

where  $S$  is the photon density ( $|E^+|^2 + |E^-|^2$ ),  $\nu_g$  is the group velocity,  $\Gamma$  is the confinement factor,  $\kappa$  is the internal absorption,  $g_n$  is the differential gain,  $N_0$  is the carrier density at transparency,  $\alpha$  is the line-width enhancement factor,  $\epsilon$  is the gain compression factor,  $t_{nl}$  is the gain nonlinearity relaxation time,  $J$  is the current density,  $d$  is the active region thickness,  $\tau_n$  is the carrier lifetime, and  $B$  and  $C$  are the bimolecular and Auger recombination rates, respectively. Gain/absorber saturation is modeled through the  $1 + \epsilon S$  term and self phase modulation through  $i\alpha$ . To account for the finite spectral gain bandwidth of the device an infinite impulse response, (IIR) filter was implemented similar to that described in [29] and [30].

Parameter values for the simulations were selected based on an InGaAs quantum well (QW)-based device, lasing at a wavelength of 1  $\mu\text{m}$ , see Table I. Using these parameter values, device dimensions, with typical currents and reverse biases in the conventional two-section gain-absorber configuration, we typically obtain pulses of 1.5–2.5 ps. These simple devices operated in the continuous wave (CW) modelocked regime giving pulses with good amplitude stability as opposed to the  $Q$ -switched mode-locked regime where the amplitude of pulses is modulated by the  $Q$ -switching envelope, following [28].

TABLE I  
PARAMETER VALUES USED IN THE MODEL

Symbol	Description	Value
$\nu_g$	Group velocity of light	$0.857 \times 10^{10}$ cm/s
$\Gamma$	Confinement factor	0.03
$\kappa$	Internal dissipative loss	$5$ cm <sup>-1</sup>
$N_0$	Carrier density at transparency	$1.2 \times 10^{18}$ cm <sup>-3</sup>
$g_{n,g}$	Differential gain at transparency (gain)	$4 \times 10^{-16}$ cm <sup>2</sup>
$g_{n,a}$	Differential gain at transparency (abs.)	$1.5 \times 10^{-15}$ cm <sup>2</sup>
$\epsilon_g$	Gain compression factor (gain)	$3.0 \times 10^{-17}$ cm <sup>3</sup>
$\epsilon_a$	Gain compression factor (abs.)	$7.7 \times 10^{-17}$ cm <sup>3</sup>
$\alpha_g$	Linewidth enhancement factor (gain)	3.2
$\alpha_a$	Linewidth enhancement factor (abs.)	1.24
$d$	Active layer thickness	0.01 $\mu$ m
$\tau_g$	Nonradiative recombination rate (gain)	10 ns
$R_1$	Reflection at gain facet	0.5
$\tau_a$	Saturable absorber recovery time	10 ps
$\Delta z$	Length of spatial integration step	2 $\mu$ m
$B$	Bimolecular recombination constant	$2.5 \times 10^{-10}$ cm <sup>3</sup> /s
$C$	Auger recombination rate	$5 \times 10^{-29}$ cm <sup>6</sup> /s
$\omega_p$	Peak frequency	$3.28676 \times 10^{14}$ /s
$a$	IIR filter parameter	0.003

### B. Hybrid Kerr Mode-Locking

As mentioned earlier, a considerable increase in the reflectivity of the nonlinear mirror is required to start pulsing, whereas only a small change can show pulse shortening if the laser is already pulsing. This is because the pulse shortening rate (mode-locking strength) is proportional to the induced reflectivity change which in turn depends on the intensity of the incident pulse. Thus, initially, as pulsing coalesces out of noise spikes, the peak intensities are low resulting in a self starting problem, (following [33], which approximates the effects of a Kerr medium as a fast saturable absorber). Therefore, a system that uses a saturable absorber to begin pulsing and a nonlinear mirror to shorten pulses is likely to be of more use than a pure nonlinear mirror laser, which would require polymers with a very large  $n_2$  value [see Fig. 3(c)]. We implement the intensity dependent reflectivity of the polymer filled mirror by replacing the standard boundary conditions with one of the form of

$$R = 0.5 + C \frac{S}{AS_{1W}} n_2 \quad (6)$$

where  $C$  is a constant determined by the slope of Fig. 4,  $S_{1W}$  is the photon density corresponding to power of 1 W and  $A$  is the waveguide area (taken to be  $5 \times 0.2$   $\mu$ m). As an accurate representation of the interaction of light with the polymer is vital to practical value of this model, we deviate from the normal method of theoretically calculating the power output from the photon density. Instead, we directly relate our modeled output power to that observed in real devices (5-mW average power for a normal two-section device), through the conversion factor in (6). The calculations assume that this corresponds to an intracavity value of approximately 10 mW (the mirror has a reflectivity of approximately 0.5). We take the waveguide confinement to be 0.6, calculated from a real device design using a commercial eigenmode solver (FIMMWAVE).

Including the wavelength dependence of the reflection from the mirrors is a very complex task and goes beyond the scope of this model. As the gainwidth of the material is usually much larger than that of the pulse, this spectral change will have little effect on the gain experienced by the pulse. However, the change

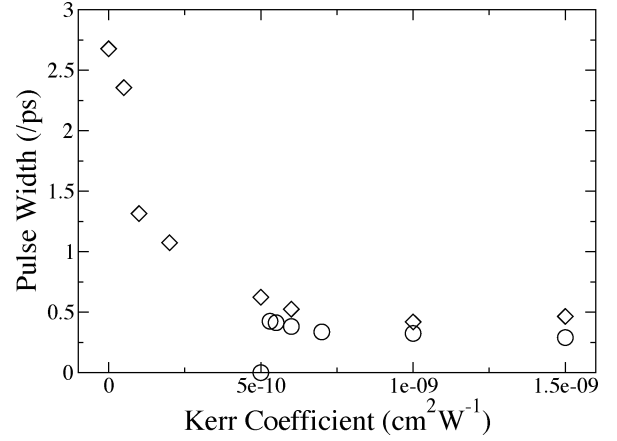


Fig. 7. Graph showing how the pulse shortens with increasing  $n_2$ . Diamonds show a hybridly mode-locked device and circles a purely Kerr mode-locked device. This was measured for devices with a gain length of 1000  $\mu$ m. The hybrid device had a saturable absorber of length 100  $\mu$ m. Note the increase in the threshold  $n_2$  for the hybrid device compared with Fig. 6.

in spectrum on reflection will perturb the pulse and would most likely result in additional chirping. It is unlikely to have more serious consequences, such as the prevention of mode-locking, as this wavelength dependent reflection will cancel out over a roundtrip limiting the effect. Furthermore, as this perturbation is related to the mirrors, it will be less important the longer the device.

There would also typically be a net dispersive effect on reflection from the mirrors (a portion will cancel out over a round trip, as for each mirror, reflection occurs on opposite sides of the bandgap), see Fig. 5. As the lasing wavelength is relatively far from the mirror band edge, the overall dispersive effects are very small, i.e., a few femtoseconds per nanometer, and are negligible compared to the effects of SPM. Our model, therefore, ignores these effects. In addition, the reaction of the polymer to the light is taken to be instantaneous.

Fig. 6 shows how the pulse duration varies with the Kerr coefficient of the polymer. For low values of  $n_2$  (less than approximately  $2 \times 10^{-11}$  cm<sup>2</sup>W<sup>-1</sup>), the strength of the Kerr mode-locking is weak compared to the effect of the saturable absorber and the pulse duration is only fractionally reduced. For values of  $n_2$  above a magnitude of approximately  $2 \times 10^{-11}$  cm<sup>2</sup>W<sup>-1</sup>, the intensity of the light is sufficient for the Kerr effect to start shortening the pulse dramatically. The nonlinear reflectivity change is governed largely by the  $n_2 S$  term in (6). This value can depend on the repetition rate of the laser—by using a longer device a higher peak power can be achieved even with the same average power output. The simulation in Fig. 6 uses a 3000- $\mu$ m gain section and a 300- $\mu$ m absorber section. If a shorter (1000  $\mu$ m) device was used, the threshold  $n_2$  for Kerr mode-locking to become noticeable would be more than doubled—see Fig. 7, (crosses). This device was also predicted to operate in the  $Q$ -switched modelocking regime—this aspect will be discussed in more detail later.

### C. Pure Kerr Mode-Locking

In this section, we look at the case where the Kerr coefficient is large enough to start mode-locking on its own. In Fig. 7, we show the results of modeling a device consisting

of a 1000  $\mu\text{m}$  gain section (no saturable absorber) with various Kerr coefficients. For comparison a similar hybridly mode-locked device is also shown. For values of  $n_2$  below approx.  $5.5 \times 10^{-10} \text{ cm}^2\text{W}^{-1}$  no pulsing is observed for the pure Kerr mode-locked case. The pulse shortening rate of a fast absorber is typically proportional to the peak intensity (and, hence, the pulsewidth) meaning the shortening rate is initially very small [3]. In a fast saturable absorber (the effect of which is simulated by Kerr-lens mode-locking [33] and our Kerr mode-locking), the pulse shortening rate is directly proportional to the inverse of the pulse duration [3], whereas the effects of a slow saturable absorber are constant with respect to the pulsewidth—the enhancing effects of higher peak powers are counteracted by the increasing ratio between the saturable absorber's recovery and the pulsewidth. Thus, a very large Kerr coefficient is required to initiate mode-locking from low peak intensities. Once pulsing begins, the peak power levels almost immediately reach a very high level, giving a very large pulse shortening rate and, hence, very short pulses, see Fig. 7. The hybridly mode-locked device always produces longer pulses than the pure case for the same  $n_2$  value (once the purely Kerr mode-locked device is above its threshold). There are two possible reasons for this: either the saturable absorber increases the magnitude and/or the complexity of the SPM induced chirp or as a result of absorption in the saturable absorber the pulse sees weaker pulse shortening as a result of its lower peak intensity. Fig. 7 demonstrates another feature of this device—the pulsewidth of the hybridly mode-locked case appears to start increasing above a certain value of  $n_2$ . The hybrid device operated in a  $Q$ -switched mode-locking regime, which typically produces peak intensities 3–4 times higher than that of the comparable CW mode-locking regime, whereas the pure Kerr mode-locked device is CW mode-locked. Thus, the hybrid device reaches a peak intensity at which the nonlinear mirror saturates and the pulse center no longer experiences any shortening effects. For sufficiently high  $n_2$ , the pure device also exhibits such behavior. However, this is a somewhat artificial problem as the mirror used in the earlier simulation was designed to amplify the effects of a weak polymer, with polymer strengths corresponding to Fig. 7, the mirror should be redesigned so that this saturation would not occur, (see Fig. 4). In general, we find the parameter ranges which result in  $Q$ -switched modelocking to be much wider in Kerr mode-locked devices (particularly so in the hybrid design) than those for standard two-section devices [28].  $Q$ -switched mode-locking is undesirable in many applications, thus in each case (i.e., for the actual  $n_2$  value) section lengths and currents should be chosen following the guidelines reported in [28]. In addition, Kerr mode-locking has the additional parameter of the position of the lasing wavelength relative to the bandgap of the nonlinear mirror. Careful adjustment of these should allow the avoidance of  $Q$ -switched mode-locking. The shortest pulses produced by the simulated devices had a duration of 290 fs, a spectral width of 7 nm and a time-bandwidth product of 0.63.

#### D. Mode-Locking Using a Resonant Polymer

If the energy of the incoming light is close to that of an excitonic resonance of the polymer, the effect of the exciton al-

ters the nonlinear response. This can result in a nonlinear refractive index which is much larger than the nonresonant value (by as much as four orders of magnitude). However, this effect is typically slower than the nonresonant case. Polydiacetylene, mentioned previously, has a relaxation time of 2 ps [21]. We incorporate this effect into our model using a simple differential equation

$$\frac{dR}{dt} = \frac{R_{\text{inst}} - R}{t_{\text{rel}}} \quad (7)$$

where  $t_{\text{rel}}$  is the polymer relaxation time,  $R$  is the reflectivity of the nonlinear mirror, and  $R_{\text{inst}}$  is the value corresponding to a polymer which reacts instantaneously. With this alteration, the system now resembles one that uses a slow saturable absorber. However, unlike the saturable absorber in the conventional two-section configuration, which typically interacts with only 3% of the light that passes through it, the polymer, as it is contained in an end mirror, can interact with most of the light, giving stronger mode-locking. This, coupled with the pulse shortening effects at the trailing pulse edge due to gain saturation (enhanced in this case due to the shorter pulse and higher peak power), allows the polymer to remain highly effective. This results in only a slight increase in pulse duration when the polymer has a nonzero relaxation time (approx. 20 fs for a relaxation time of 5 ps). Polydiacetylene has a crystalline form and as a result, it is likely that incorporation into the mirror may cause a significant reduction in the  $n_2$  value (involves the use of nanocrystals suspended/dissolved in a polymer). However, our modeling shows that significant shortening may be observed for an  $n_2$  as low as  $10^{-10} \text{ cm}^2\text{W}^{-1}$ . This is two orders of magnitude less than the maximum recorded value, and should be achievable in practice.

#### IV. CONCLUSION

In this paper, we have proposed a design for a monolithic diode laser capable of producing subpicosecond pulses. As demonstrated by Tropper *et al.* [15] and Martins-Filho *et al.* [7], increasing the mode-locking strength is an effective means of shortening pulses. The device considered here makes use of perhaps the strongest possible form of mode-locking, i.e., Kerr effect mode-locking.

Whereas the lithographic tuning required to fabricate the photonic bandgap mirrors to the required tolerance and the incorporation of a suitable polymer will entail much time and effort, the currently available technology is sufficient to produce devices with better performance than those available using only a reverse biased section as the saturable absorber. Here, we have considered a stripe geometry laser, as this is most suited (by its relative ease of fabrication) to the experimental realization. However, using buried heterostructure lasers, a much higher power concentration may be achieved (potentially a better than five-fold improvement). This would widen the range of the suitable polymers, increasing the possibility of finding one with suitable characteristics (physical properties such as solubility, damage resistance, etc).

It should be noted that as the model does not include terms to describe ultrafast processes which become important for subpicosecond pulses, such as those related to the finite intraband

relaxation time (100 fs), and the effects of the complicated reflection of the mirror, we expect, in practice, that the produced pulses would be somewhat longer than those predicted. However, it seems reasonable to believe that the nonlinear chirping that may ensue, will be relatively weak in magnitude (if not complexity) [15], suggesting that Kerr mode-locking has a strong possibility of overcoming it.

The time-bandwidth product of the simulated pulses was typically twice the transform limit. Increasing the mode-locking strength results in only a slightly shorter pulse with approximately the same time-bandwidth product. This suggests that some form of dispersion compensation is necessary to efficiently shorten the pulse further.

We have demonstrated the potential of Kerr mode-locking using three very different forms of polymers. Whereas the problem of photostability remains, the versatility of this design gives the possibility of finding a polymer with the desired properties.

Whereas as the proposed device is of a complex nature, requiring demanding fabrication, it is, to the best of our knowledge, the only such device, theoretical or experimental, which has the potential to overcome the considerable obstacles presently preventing the realization of a true monolithic femtosecond diode laser.

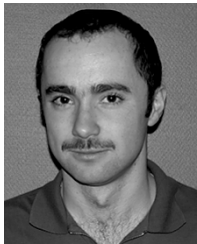
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