

Integrated chirp compensation in a monolithic passively mode-locked semiconductor diode laser

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We present traveling wave numerical simulations of passively mode-locked diode lasers that incorporate chirp compensation monolithically using a Fabry-Pérot interferometer, which provides a negative group delay. Numerical results show pulse compression of up to 65%. Time-frequency domain study of the pulses reveal a significant reduction in chirp across the pulse. Limitations of this simple linear chirp compensation scheme are examined. © 2005 American Institute of Physics. [DOI: 10.1063/1.1940728]

Passively mode-locked monolithic diode lasers are an attractive method of ultrashort pulse generation due to their ease of fabrication, low-cost, extreme compactness, mechanical stability, and high repetition rates. Monolithic devices have routinely generated pulses of 2–5 ps since their first demonstration in 1989.¹ Semiconductors lasers have sufficiently broad spectral gain bandwidths to support pulses of approximately 100 fs but self-phase modulation (SPM) induced chirp, due to the large linewidth enhancement factor, prevents this spectral bandwidth from being used efficiently and results in longer pulse durations. Chirp and dispersion compensation have been used extensively to compress pulses in external cavity semiconductor lasers with great success but has never been incorporated into a monolithic device.

Due to the high refractive index contrast in deeply etched structures it can be difficult to fabricate chirped mirrors as reflection occurs over just a few periods. Shallow etching allows for more control over the chirp, but due to their length scales of several hundreds of periods, this would require additional contacts to avoid absorption in the unpumped region. Therefore, it is useful to consider a simple form of chirp compensating element that can be fabricated with ease.

We have chosen to examine the incorporation of a Fabry-Pérot interferometer (FPI) into the laser. A schematic diagram of the device considered is depicted in Fig. 1. The FPI consists of a front mirror of reflectivity R , a cavity of length d , and a backmirror that consists of a simple cleaved facet. Such a cavity can be fabricated by etching a slot of suitable thickness between the FPI and the absorber. A plot of the phase shift on reflectance from the FPI and group delay versus wavelength for $R=55\%$, corresponding to an etched slot of 200 nm length at a wavelength of 1.55 μm , is shown in Fig. 2 ($d=8\ \mu\text{m}$). The Fabry-Pérot resonances corresponding to the cavity length result in the obvious periodic phase discontinuities. Alternatively, a series of dielectric coatings could be applied to the slot walls to obtain the required reflectivity.²

We model this device using an adapted form of the traveling wave model presented in Ref. 3. The traveling wave model includes the effects of gain dispersion and compression, spatial and spectral hole-burning, colliding pulse ef-

fects, SPM, and gain nonlinearity relaxation times. We simulate a device with a gain section of length 1 mm, saturable absorber of length 100 μm with absorber recovery time of 35 ps, and gain section current of 50 mA. Additional parameters that correspond to a 1.55 μm InGaAs-InGaAsP-InP device are taken from Ref. 4.

We performed numerical simulations of a device with various d and R . The effect of absorption in the FPI was included and found to be negligible. A cavity length of 8 μm led to the shortest pulse durations for this level of pumping and we consider this value of d for the remainder of this letter. In the absence of the FPI the device considered produces pulses of 2.49 ps in duration. This pulse duration was reduced to 960 fs when $R=55\%$ (Fig. 3). This reflectivity dictates the finesse of the group delay trough in Fig. 2(b), which must be matched by the pulse spectral width to provide optimized compensation. The pulse duration increased smoothly as R and or d was varied either way, because the cavity chirp and dispersion relationship were no longer suitably balanced. To understand this balance within the cavity we calculated the group delay experienced by an optical pulse propagating through just the absorber and gain sections over a round trip by examining the phase shift of the pulse's spectrum before and after. This group delay was calculated to be approximately +120 fs at the operating wavelength which closely matches the magnitude but has the opposing sign to that of the FPI displayed in Fig. 2. The origin of this group delay is primarily due to SPM. An exact match between the chirp and dispersion is unexpected due to the different spectral shapes of the two effects.

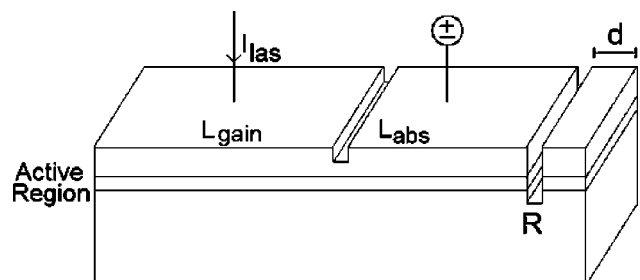


FIG. 1. Diagram of monolithically passively mode-locked diode laser comprising a gain section, a reverse biased saturable absorber, and FPI for chirp compensation.

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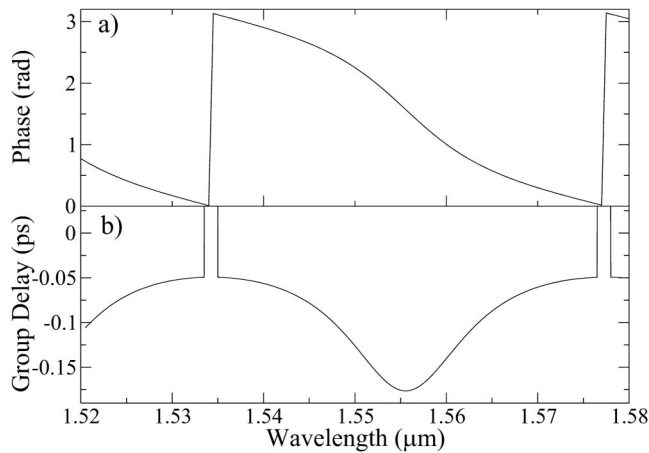


FIG. 2. Plot of (a) phase shift on reflectance from FPI and (b) group delay vs wavelength for front mirror reflectivity of 55%.

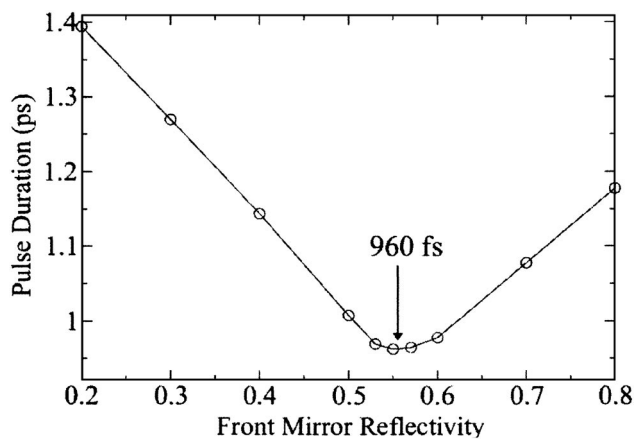


FIG. 3. Plot of pulse duration vs FPI front mirror reflectivity.

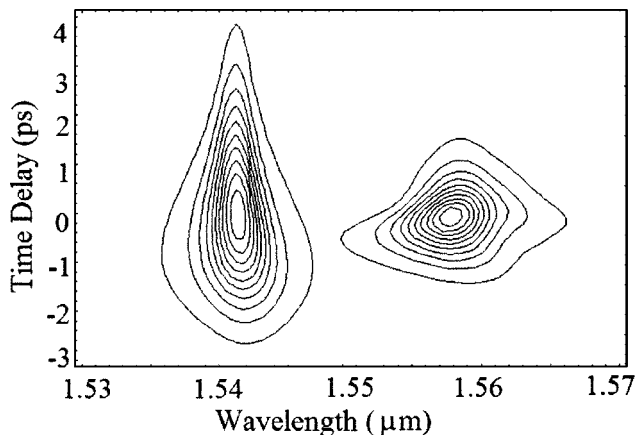


FIG. 4. Plot of numerical sonogram of uncompensated 2.49 ps pulse (on left) and compensated 960 fs pulse (on right).

The time bandwidth product of the pulses changed from a value of 1.1 without the FPI to a value of 0.7 with the chirp compensation. This indicates a significant reduction in chirp and a more efficient use of the gain bandwidth, however, this

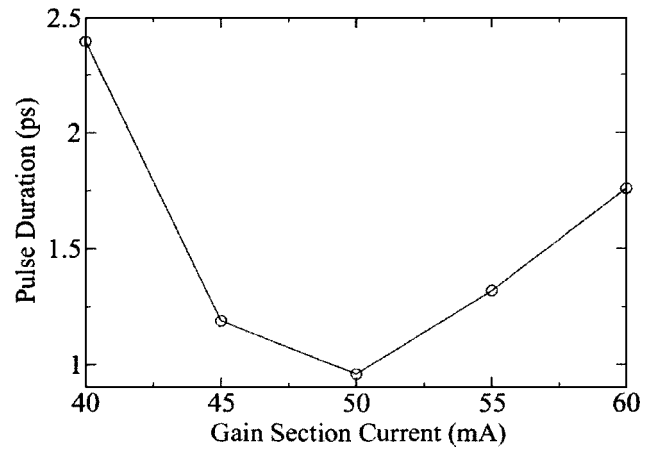


FIG. 5. Pulse duration tuning in chirp compensated optimized device with gain section current.

is still higher than the Fourier transform limit. This is due to the simple nature of the FPI compensation that is not able to compensate the higher order phase components of the pulse due to its nonlinear chirping.

To extract spectral and temporal data from our simulations we performed numerical sonograms, using a causal wavelet transform,⁵ on the uncompensated and compensated pulses (Fig. 4). The uncompensated pulses have a much longer duration and significant chirping. In the compensated case, the chirp is much less and is in the opposite direction. We also observe that the compensated pulse has been shifted in wavelength to the maximum negative group delay of the FPI, as would be expected.

Rf spectra of the compensated pulse trains yield the discrete cavity modes spaced at frequencies corresponding to the cavity repetition rate. There is also a modulation in amplitude at the frequency corresponding to that of the 8 μm FPI cavity. Variation in R results in a change in the modulation depth of the FPI frequency component.

Figure 5 reveals the effect on pulse duration with gain section pumping current which offers the potential of a pulse duration tunable source. A change to this current leads to a change in the chirp across the pulse due to the SPM sensitivity to change in photon density. This results in a different chirp and dispersion balance within the cavity that is no longer optimized. It is possible to reoptimize the FPI cavity by varying R and d .

In conclusion, we have presented practical design considerations for the fabrication of a monolithic chirp compensated passively mode-locked diode laser that produces subpicosecond pulses.

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