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Dispersion measurements of a 1.3 μm quantum dot semiconductor optical amplifier over 120 nm of spectral bandwidth

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Group delay and higher order dispersion measurements are conducted on a 1.3 μm quantum dot semiconductor optical amplifier at various injection currents. White-light spectral interferometry is performed, along with a wavelet transform to recover the group delay. The group delay, group velocity dispersion, and higher order dispersion terms are quantified. The measurement spans both ground state and first excited state transitions, ranging from 1200 to 1320 nm. The group velocity dispersion, β_2, is found to be -6.3×10^3 fs^2 (7.6 fs/nm) at an injection current of 500 mA. © *2010 American Institute of Physics*. [doi:10.1063/1.3430742]

Semiconductor quantum dot materials have gained widespread attention for use as sources in mode-locked lasers. Large gain bandwidth, wide variability of linewidth enhancement factor, low chirp, relatively low sensitivity to temperature fluctuation, and high modulation bandwidth have been cited as advantages over quantum well devices.[1] Their large gain bandwidth, which can be greater than 15 THz, is especially attractive for the generation of broad mode-locked laser spectra, with the potential for transform limited pulse widths of less than 100 fs. This capability is attractive for many applications including high speed communication and signal processing.[2]

Semiconductor optical amplifier (SOA) gain is controlled by current injection, which also results in a change in the carrier concentration in the active region. The complex index of refraction of a medium is known to be dependent on the carrier concentration in the medium. Therefore, changing the gain in a laser cavity changes the mode spacing of a mode-locked laser. As the SOA gain is often one of the key elements determining both the static and dynamic dispersion of a mode-locked laser, it is important to have a clear understanding of the dependence of the dispersion and its higher order terms on injection current. This information can be used in determining the proper dispersion compensation techniques for broad bandwidth mode-locked laser sources.

A Taylor expansion of the propagation constant, β, provides a set of coefficients which is used to quantify the dispersive properties of the SOA. $\beta(\omega)$ is related to the spectral phase by the following:

$$\beta(\omega)=\frac{\Phi(\omega)}{L}=\frac{\omega/c\cdot n(\omega)}{L}, \tag{1}$$

where $\Phi(\omega)$ is the spectral phase, L is the length of the medium, and n is the frequency dependent refractive index. Taking the first derivative yields the following:

$$d\beta/d\omega=\frac{d\Phi/d\omega}{L}. \tag{2}$$

This is the group delay over the length of the device, the quantity measured in this work. The expansion of β is

$$\beta=\beta_0+\beta_1(\omega-\omega_0)+\frac{1}{2!}\beta_2(\omega-\omega_0)^2+\frac{1}{3!}\beta_3(\omega-\omega_0)^3+\dots, \tag{3}$$

and its derivative is

$$\frac{d\beta}{d\omega}=\beta_1+\beta_2(\omega-\omega_0)+\frac{1}{2!}\beta_3(\omega-\omega_0)^2+\dots, \tag{4}$$

where the first term is constant in frequency, representing the path length difference of the interferometer arms. By fitting the acquired group delay curve to Eq. (4), the group velocity dispersion, β_2, and higher order dispersion terms are determined.

White-light interferometry has been used for dispersion characterization of a wide variety of materials.[3–5] The technique uses a Michelson or Mach–Zehnder style interferometer with a broadband light source (Fig. 1). The light is divided into a reference beam and another which passes through the device under test. The beams are recombined and the spectral phase is determined by the interference of the beams. Interference can be measured either temporally, with a movable mirror and single photodetector or spectrally, by keeping the relative path length difference static, and spatially separating and detecting spectral components with a spectrometer. The static version, used here, has no moving parts and is preferable under the condition that a spectrometer with sufficient resolution is available.

The interference spectrum, shown in Fig. 2, has sinusoidal fringes which vary in periodicity due to the different phase delays arising from a frequency dependent refractive

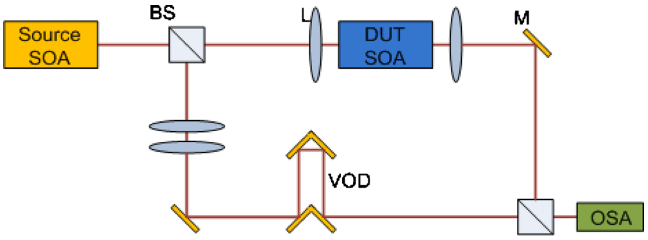

FIG. 1. (Color online) Mach–Zehnder style, spectral interferometer experimental setup; SOA, semiconductor optical amplifier; DUT, device under test; BS, beam splitter; L, coupling lens; M, mirror; VOD, variable optical delay; and OSA, optical spectrum analyzer.

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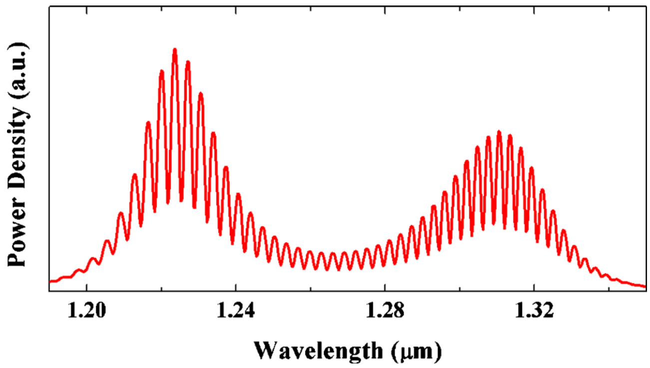

FIG. 2. (Color online) Spectral interferogram. Group delay is obtained by determining the change in fringe spacing across the spectrum.

index. By finding the local periodicity at each point in the interferogram, the group delay of the device under test is determined.[6]

Traditionally, the Fourier transform technique is used to recover the spectral phase of the signal and numerical differentiation is then required to calculate the group delay. This process often requires smoothing functions to reduce the amplification of noise in the data. Numerical differentiation and smoothing functions can be avoided by the use of the wavelet transform (WT). As shown by Deng *et al.*,[7] a WT will extract the group delay directly from the interferogram. While this method requires more processing time than the Fourier transform method, it is handled readily by current desktop computers.

To calculate the WT, the overlap integral of the interference spectrum and a user-defined wavelet function with a known periodicity is calculated. The wavelet period is varied to find the period for which the overlap integral is maximized. This is done for each measured frequency in the interferogram. The result is the local periodicity at each point in the interferogram, i.e., the group delay. Figure 3 shows the WT result, a contour plot where the maximum at each wavelength value corresponds to the group delay value for that wavelength.

Interference spectra are acquired using a Mach–Zehnder interferometer. This configuration, shown in Fig. 1, is chosen for ease of alignment and to measure the group delay on a single pass through the sample. The light source is a 3 mm SOA fabricated from the same wafer as the 2 mm SOA under test.

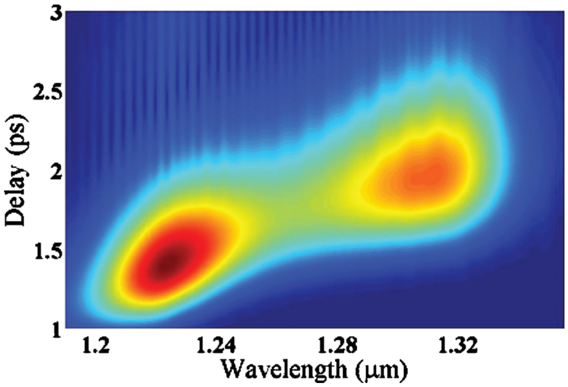

FIG. 3. (Color) WT of spectral interferogram. The maximum at each wavelength value corresponds to the group delay.

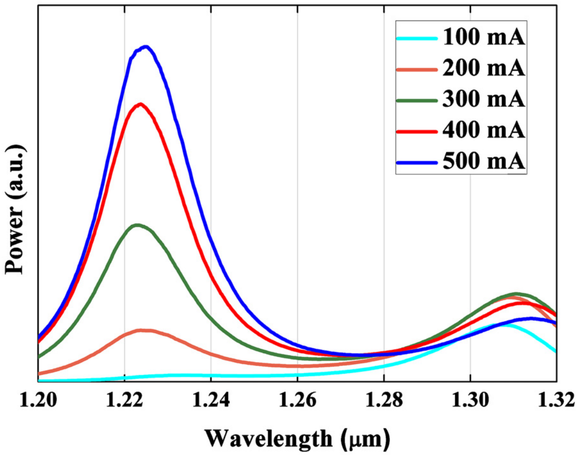

FIG. 4. (Color online) QD SOA spectral density at measured injection currents.

Dispersion characteristics are measured for a ten layer InAs/GaAs quantum dot SOA with a 4 μm wide waveguide. The uncoated facets were fabricated at a 7° angle to minimize reflections. The device is mounted p-side up on a copper stud with gold coating for electrical and heat conductivity. A thermoelectric cooler and thermistor are used to for temperature stabilization.

The SOA is placed between two microscope objective collimating lenses. An identical pair of lenses is placed in the reference arm of the interferometer to compensate for the dispersion induced by the lenses. In order to observe the group delay dependence on injection current, the device is measured at injection currents ranging from 100 to 500 mA.

A gold rooftop mirror on a micrometer stage is placed in one interferometer arm for use as a variable optical delay to control the path length difference between the two interferometer arms.

It is necessary to first take a measurement with only the lens pairs in each arm to calculate the background group delay arising from bias in the interferometer.[8] Bias arises from optical path length mismatch caused by mirrors and lenses which are not identical, imperfections in the beam splitters and a small amount of dispersion caused by the free space path length difference. The group delay bias was found to deviate less than 10 fs from the average value in the region of interest, spanning 120 nm.

The group delay for the SOA (Fig. 4) shows anomalous dispersion with 800 fs differential delay across the measured spectrum. Delay is seen to decrease with increasing injection current, though not uniformly across the spectrum. The decrease is most pronounced near the first excited state peak (1.23 μm), changing by approximately -15 fs per 100 mA. The ground state (1.31 μm) exhibits less of a dependence on injection current, changing by -15 fs over the entire 400 mA increase.

The magnitude of the group velocity dispersion tends to increase with injection current. Under 100 mA of injected current, β_2 is -5.7×10^3 fs^2 (6.7 fs/nm) where, at 500 mA, it is -6.3×10^3 fs^2 (7.6 fs/nm). This amount of dispersion is of the same order of magnitude as that of other semiconductor materials and devices,[8,9] after normalizing for injection current and device length.

In addition to the large linear dispersion of the group delay, higher orders are observed. The Taylor expansion of

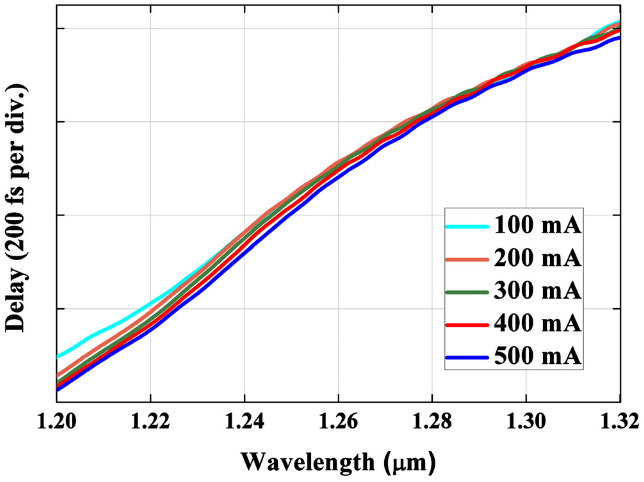

FIG. 5. (Color online) Group delay at measured injection currents.

group delay with 500 mA of injection current shows measurable quadratic, cubic, and higher order dispersion: $\beta_3 = -4.0 \times 10^4\ \mathrm{fs}^3$, $\beta_4 = 1.3 \times 10^6\ \mathrm{fs}^4$, and $\beta_5 = 4.6 \times 10^7\ \mathrm{fs}^5$. The cubic dispersion is evident in Fig. 5 by a change in concavity, from concave up at short wavelengths, to concave down at longer ones.

In summary, the dispersion characteristics of an InAs/GaAs quantum dot SOA at various injection currents are investigated. These results show a predominant anomalous dispersion with measurable higher order terms. The Taylor expansion coefficients for the dispersion of the device at 500 mA of injected current are $\beta_2 = -6.3 \times 10^3\ \mathrm{fs}^2$, $\beta_3 = -4.0 \times 10^4\ \mathrm{fs}^3$, $\beta_4 = 1.3 \times 10^6\ \mathrm{fs}^4$, and $\beta_5 = 4.6 \times 10^7\ \mathrm{fs}^5$. Also, while the group delay decreases with increasing injection current, the magnitude of the group velocity dispersion increases. Of most significance, if these devices are to be used for ultrashort pulse generation, care must be taken to compensate for this higher order dispersion in order to maximize the mode-locking bandwidth.

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