Tunable ultraslow light in vertical-cavity surface-emitting laser amplifier

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Abstract: We report the experimental demonstration of tunable ultraslow light using a 1.55 um vertical-cavity surface-emitting laser (VCSEL) at room temperature. By varying the bias current around lasing threshold, we achieve tunable delay of an intensity modulated signal input. Delays up to 100 ps are measured for a broadband signal with modulation frequency of 2.8 GHz. With a VCSEL design optimized for amplification and leveraging the scalability of VCSEL arrays, delays of multiple modulation periods are feasible.

OCIS codes: (999.9999) Optical buffering; (250.5980) Semiconductor optical amplifiers; (250.7260) Vertical-cavity surface-emitting lasers

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1. Introduction

Recently, there has been tremendous interest in variable all-optical delay lines and buffers for applications in optical communications, phased-array antennas and optical signal processing [1-5]. Circumventing optical-electrical-optical (OEO) conversion has the potential for increased capacity and throughput, and reduced latency in future optical networks. The key towards implementations of compact optical buffers lies inherently in achieving controllable ultraslow propagation of high-frequency modulated optical signals. Over the last couple of years, slow light has been demonstrated in a variety of systems using approaches based on material or waveguide dispersion [6-9]. While differing in their underlying physical mechanisms, the approaches share fundamental limitations with respect to the maximum achievable delay-bandwidth product. In addition, most demonstrations exhibit limited bandwidth not suited to accommodate broadband signals in the GHz-range, as required in most communications applications. This is one main reason why, up to this point, all-optical buffers still do not exist in practice.

In this paper, we report the use of a VCSEL operated as Fabry-Perot (FP) amplifier [14] to achieve tunable group delays for broadband signals at room temperature. We demonstrate up to 100 ps tunable delay of a 2.8 GHz modulated signal. Given the VCSEL active region of 30 nm this delay corresponds to a slow down factor of 10^6. The delay-bandwidth product is 0.36, corresponding to the largest achieved for semiconductor-based devices, to the best of our knowledge. As multiple-wavelength tunable arrays have already been demonstrated in VCSELs [12, 13], the results are promising to scale up the tunable delay to broadband signals and larger fractional delays. Tuning of the group delay is achieved by controlling the gain inside the VCSEL active region by varying the bias current around threshold. While we observe optical delay within a FP amplifier regime, i.e. below lasing threshold, we note that increased delays can be achieved by pushing the operating regime into what we consider to be the onset of injection locking. Although the observed delay of 100 ps on a 2.8 GHz sinusoidal modulation still presents 36% of the modulation period, note that the scalability of the approach is promising for delays of several modulation periods [12-14]. Room-temperature operation and ease of control make this a practical approach for a compact optical buffer device.

2. Experiment

The VCSELs used in this experiment are single-mode, buried tunnel junction (BJT) VCSELs emitting at 1550 nm [10, 11]. The BJT structure is ~ 5×6 μm, which provides both carrier confinement and index guiding. The active region consists of five InGaAlAs/InP quantum-wells (each of 6 nm thick). The front and back mirror reflectivity are 99.4% and 99.75%, respectively. The probe signal is generated by a tunable laser (SDL 8610) modulated with an external Mach-Zehnder interferometer (MZI) electro-optic modulator. A RF-synthesizer is used to drive the modulator.

As shown in Fig. 1, the VCSEL is operated in reflection mode. The power of the signal laser incident on the VCSEL can be adjusted by an optical attenuator. By means of a polarization maintaining (PM) optical circulator (OC) the signal is coupled into as well as coupled out the VCSEL cavity in the reflection direction. The output of the OC is split into two branches. One branch, used for measuring the group delay, passes through an Erbium-doped fiber amplifier (EDFA) before being detected by a photo-receiver. A fast oscilloscope displays the detected modulation traces. The second branch is used to monitor the VCSEL /

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signal spectrum and power with an optical spectrum analyzer (OSA) and optical power meter. To synchronize the oscilloscope and set a reference for the time delay, half of the modulation signal is fed into the trigger input.

The parameters we varied in this study include the bias current of the VCSEL (I_{bias}), the optical power of the signal input (P_{sig}) and the MZI modulation frequency (f). We operate the VCSEL in the bias current range of I_{bias} ~ 0.9 I_{th} - 1.05 I_{th}. The probe laser power is adjusted such that the incident power P_{sig} is on the order of the spontaneous emission from the VCSEL below threshold. A single-tone sinusoidal signal rather than pulsed signal is used to drive the modulator, due to the limitation (bias drift) of our MZI modulator. The frequency range we studied is also limited by the modulator to 1~3 GHz. Time delay as a function of modulation frequency and VCSEL bias are measured.

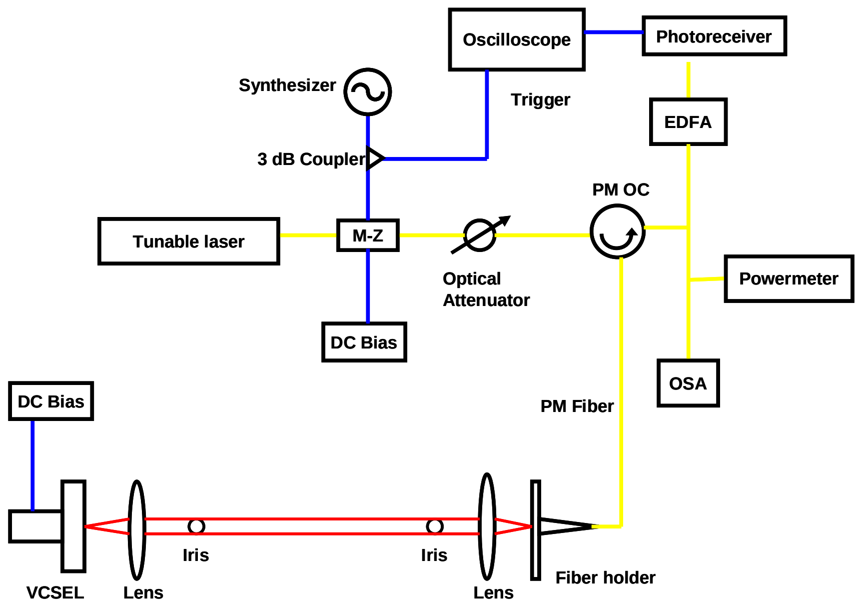

Fig. 1. Experiment setup. A tunable laser (SDL 8610) provides the probe signal and is modulated using a Mach-Zehnder interferometer. The optical attenuator is used to adjust the signal power. PM OC and fibers are used to couple the light into the VCSEL cavity. Time domain measurements are carried out using a fast photo-receiver and oscilloscope. An EDFA is used to amplify the reflected signal. The optical spectra and power levels are monitored by OSA and power meter respectively. (M-Z: Mach-Zehnder interferometer, PM: polarization maintaining, EDFA: Erbium-doped fiber amplifier, OSA: optical spectrum analyzer.)

3. Results

Figure 2 shows signal reflection spectra as a function of frequency difference (detuning) between the VCSEL and the signal laser (f_{VCSEL}-f_{Probe}) for various VCSEL biasing conditions. No modulation is imposed on the single mode output of the SDL laser for these measurements. The inset shows the light-current (L-I) characteristics of the VCSEL revealing a threshold at about 1.15 mA. The spectra in Fig. 2 are taken at a fixed input signal power P_{sig}, measured to be approximately 100 nW. Comparison with the L-I characteristics shows that the signal input power is on the same order as the VCSEL emission around threshold.

With the VCSEL bias turned off, we observe a reflection dip as expected for a cold FP-cavity. As we increase the VCSEL bias current, we observe a transition from a reflection dip to a reflection peak, tracking the evolution from cold-cavity to an amplifier operating regime. For bias currents still below threshold (~1.15 mA) a symmetric profile of the reflection spectrum centered at zero detuning is observed exhibiting a FWHM ~5.3 GHz. This FWHM

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is relatively narrow because the device is designed as a VCSEL to have low threshold current, rather than as an amplifier. When the bias current is increased to 1.3 mA, i.e. above threshold, the reflection spectra become asymmetric. We interpret this transition in the spectra to be marking the onset of injection locking. This is supported by the fact that the VCSEL is actually lasing and the fact that the steep edge occurs at positive wavelength detuning is in agreement with the well-known asymmetry of the locking range [15].

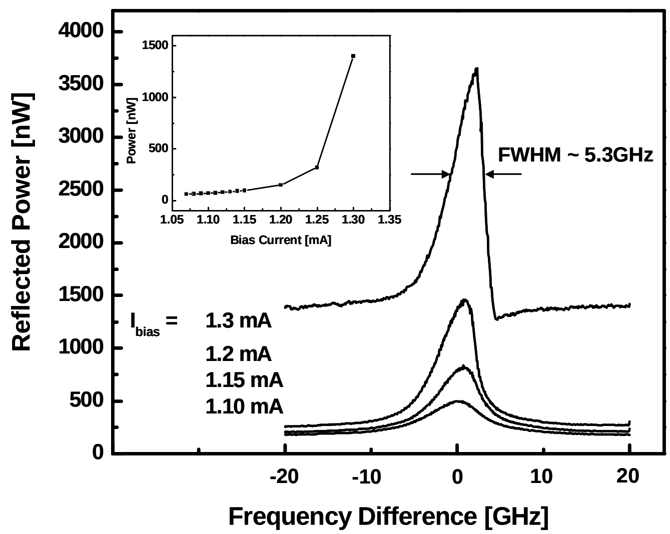

Fig. 2. Optical spectra taken by sweeping the tunable laser frequency at various VCSEL biases. Spectra are taken when the VCSEL is biased around threshold (1.15mA) and the asymmetric profile indicating it is lasing, while symmetric profile indicating it is in the amplifier regime.

Time domain measurements are performed by imposing a sinusoidal intensity modulation in the range of 1~3 GHz onto the probe laser and the time delay of the RF-modulation are measured for various VCSEL bias currents and detuning. The VCSEL lasing wavelength increases with bias current, primarily due to thermal effects. The change is about 2.1 GHz (0.0168 nm) when its bias is changed from 1.10 mA to 1.3 mA. Due to the lack of a temperature stabilizing station for the VCSELs in this experiment, we fine tune the probe laser to track this change. This will not impact future practical implementation, as the VCSEL can be wavelength stabilized. The frequency of 3 GHz is slightly larger than the VCSEL amplifier bandwidth and limited by our instrumentation (modulator). The time-domain reference trace is taken with the VCSEL switched off, and the signal wavelength away from the VCSEL resonance. The maximum delay is achieved with the probe laser frequency tuned to the resonance of the VCSEL cavity and the VCSEL biased around threshold.

Figure 3 shows the delayed modulation traces at 2.8 GHz for various VCSEL bias currents. Corresponding reflection spectra are shown in Fig. 2. With increasing bias currents, we observe increased delays of the RF-modulation. Once the VCSEL is biased around threshold, we observe a "clamping" of the RF-gain followed by a clamping of the delay at slightly higher bias currents. This feature is highly desirable for many applications. The maximum group delay of 100 ps is observed when the VCSEL is biased slightly above lasing threshold as shown in Fig. 3. Given the VCSEL active region of 30 nm this delay corresponds to a slow down factor of 10^6. Note that the RF-amplitude of the modulation remains within 4 dB over the entire tuning range of delays as shown in Fig. 3.

Figure 4 shows time delay for another VCSEL operated in the same set-up and similar operating condition with three signal modulation frequencies, f = 1.0, 2.0 and 3.0 GHz. The

VCSEL bias current is at $0.9I_{th}$ and probe signal power approximately 200 nW. Time delays of 122 ps, 90 ps and 90 ps were obtained for 1.0, 2.0 and 3.0 GHz, respectively. The corresponding time-bandwidth ratios are 0.12, 0.18 and 0.27, respectively. This frequency dependence would certainly translate into pulse distortion and dispersion. However, it may be possible to reduce the frequency dependence by optimizing various designs and operating parameters. A more systematic study is currently under investigation.

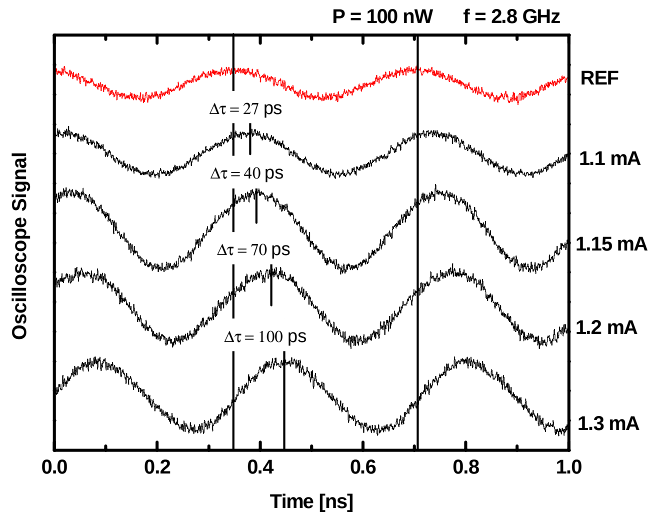

Fig. 3. Measurements of delay for a RF-modulated optical signal (f = 2.8 GHz) at various VCSEL bias conditions around threshold. The probe laser power is fixed at zero detuning, P = 100 nW. The reference waveform in red is taken when the VCSEL is off. Delays increase with increasing VCSEL bias current.

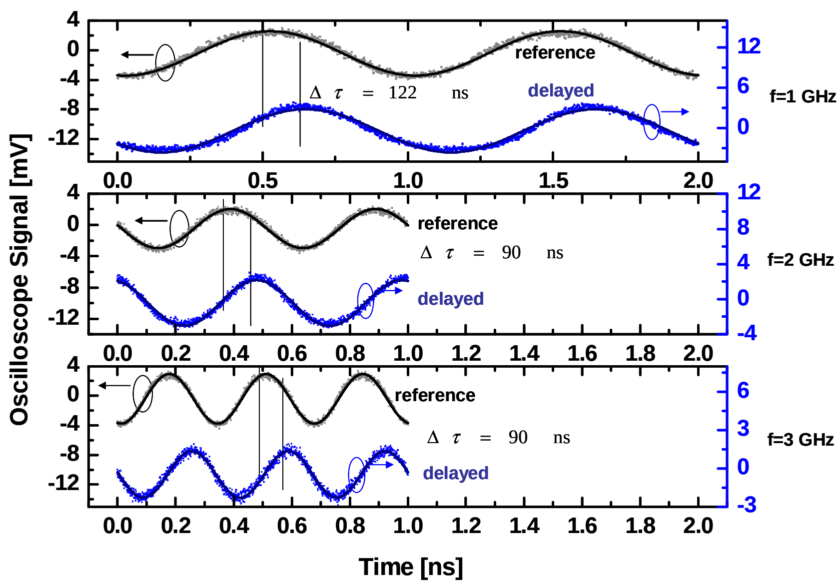

Fig. 4. Measured delay waveforms at modulation frequencies 1, 2, and 3 GHz with VCSEL biased at $0.9I_{th}$, and fixed signal power 200 nW. The dotted lines are measured data, while the solid lines are fitted data.

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4. Discussion

The performance characteristics of VCSELs in amplifier mode have been discussed extensively using a rate equation model for describing the dynamics of the carrier density and photon number density in the lasing mode [14]. The discussion there is limited to bias currents below threshold, more precisely $I_{bias} = 0.95\ I_{th}$. In this regime, Kramers-Kronig (KK) relation predicts a positive dispersion of the phase tied to the gain feature of the VCSEL amplifier e.g. in reflection. For a linear causal system, a linear increase of the delay with increasing gain is thus expected and this is what we observe for bias currents below threshold. Clearly, this picture fails once the VCSEL is lasing. This manifests in our experimental results in the fact that delay and RF-gain seem no longer to be correlated for bias currents in the range 1.15 mA to 1.30 mA, i.e. around and above threshold. While delay increases from 40 to 100 ps in this bias current range, almost no change in RF gain is observed. Note in this context, that the spectra shown in Fig. 2 are reflection spectra, which result from a superposition of the signal input reflection and the VCSEL emission. The spectra only relate to the gain spectra of the VCSEL amplifier, if the VCSEL is biased below threshold.

Experimental observation reveals thus that by pushing the operating conditions into an injection locking regime, delays beyond those achievable in a VCSEL amplifier regime can be achieved with the benefit of reduced changes in RF-gain. We tentatively attribute the origin of the group delay in injection locking regime to asymmetric sidemode suppression, which results from the asymmetry of the locking range and which affects phase modulation of the signal input [16, 17]. In addition to low RF-gain variation, shifts of the cavity resonance due to changes in the refractive index are negligible due to the small changes in bias current necessary to achieve the delay range in the low-threshold current VCSELs, (see Fig. 2). Both of these present major advantages over edge-emitting lasers (EEL) used in amplifier mode to achieve tunable group delays. For EEL, operation near critical coupling is necessary to guarantee small variations in RF-gain. Also, large frequency shifts are induced by tuning of the bias current [18]. Both result in limited tunability of the delay.

Finally, we would like to note that there is significant advantage of operating an optical buffer in a gain rather than a loss element to achieve slow light. One obvious outcome is that the signals may propagate longer distances. The noise associated with amplifier-based slow light, however, requires further study and is beyond the scope of this paper. The noise analysis and trade-offs are expected to be similar to that of a typical Fabry-Perot semiconductor optical amplifier. Design optimization is necessary to achieve higher delay-bandwidth product at high modulation frequency. A gain bandwidth of VCSEL amplifier on the order of THz was previously predicted [14]. Accordingly, we anticipate increased bandwidth with proper device optimization.

5. Conclusion

Continuously tunable ultraslow light is achieved using a vertical-cavity surface-emitting laser (VCSEL) at room temperature. Tunable delays up to 100 ps for a 2.8 GHz modulated signal with only 4 dB variation in RF-gain over this tuning range are demonstrated. While operating as a VCSEL amplifier below threshold, additional group delay can be achieved by operating the VCSEL above threshold in an injection locking regime. The delay-bandwidth and storage-bandwidth products are 0.36 and 1×10^9 Hz, respectively. The delay-bandwidth product is the largest achieved for semiconductor based devices, to the best of our knowledge. The results are promising for larger tunable delay and higher bandwidth signals with the use of multi-wavelength VCSEL arrays.

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