SHORT PULSE GENERATION USING SEMICONDUCTOR LASERS

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ABSTRACT

We have generated picosecond optical pulses with very pure spectral characteristics using semiconductor lasers with monolithic cavities. For repetition rates less than 10 GHz, gain-switching of DFB lasers with quantum well loss-gratings is used. Monolithic colliding pulse mode-locked semiconductor lasers are used to generate short pulses with repetition rate up to 350 GHz.

1. INTRODUCTION

The generation of ultra-short optical pulses and its synchronization to electronic oscillators are of great interests to many optoelectronic applications such as high bit rate time-division multiplexed communication systems, ultra-long distance soliton fiber transmission experiments[1], picosecond optical logic gates[2], opto-electronic sampling systems[3], and broadband sub-millimeter-wave generation[4]. Theoretically, it is possible to generate very short optical pulses (~ 50 femtoseconds) in semiconductor gain medium because of its broad gain spectrum (~ 1000 Å). The minimum pulse width that can be generated for a prescribed spectral bandwidth is limited by the Fourier theorem. A transform-limited optical pulse would have very small frequency chirp and very little amplitude substructures and can propagate a long distance in dispersive mediums such as fibers.

Gain switching and mode-locking are two commonly used methods to generate short optical pulses from semiconductor lasers. Gain switching of a laser diode is easily achieved by capitalizing the first period of the relaxation oscillation which is generated by switching on a diode laser biased just below threshold[5,6] with injected electrical or optical excitations. The advantage of using the gain switched pulses is the flexibility to change the repetition rate without modifying the cavity length. However, when the laser is suddenly switched from below to above threshold, significant fluctuations in both the carrier density and the time delay between the excitation and optical output are produced. These produce significant frequency chirp[7] and timing jitter associated with the gain-switched optical pulses[8].

To generate short optical pulses with very pure spectral properties and low timing jitter, mode-locking techniques are generally utilized. The semiconductor media provide both the gain and absorption mechanism which are needed for mode-locking. Earlier works have utilized semiconductors in implementing active (forced) mode-locked, passive mode-locked, and hybrid mode-locked lasers using external resonant cavities and bulk optical elements[9]. Because the pulse shaping mechanisms are determined by the difference in transient saturation and recovery time constants between the gain and absorber in a mode-locked laser[10], it is possible to generate short optical pulses with a repetition rate beyond the relaxation oscillation frequency of the semiconductor laser. In this paper, we demonstrated the short pulse generation with nearly transform-limited spectral quality by either gain-switching of DFB lasers with integrated loss-gratings or using colliding pulse mode-locked (CPM) quantum well lasers with integrated cavities.

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2. GAIN-SWITCHED DFB LASERS WITH QUANTUM WELL LOSS GRATINGS

The generation of single mode short optical pulses by semiconductor distributed feedback (DFB) laser with near transform-limited bandwidth product at infrared wavelength is very important for many applications in fiber communication systems. Commonly-used index-coupled semiconductor distributed feedback lasers have problems to yield single mode radiation from the uncertainty of gratings-to-facet phases[11,12]. Recently, lots of interests have been generated by the gain-coupled DFB lasers which promise high single mode yield, immune to residual facet reflection, and resistance to external reflections[13,14]. Short optical pulses have also been generated by gain-coupled DFB lasers with low wavelength chirping[15]. Previously, we have demonstrated excellent lasing characteristics from gain-coupled DFB lasers by introducing quantum well (QW) loss-gratings grown by chemical beam epitaxy (CBE)[16]. Good and reproducible control of coupling coefficient, and large side-mode suppression ratio have been obtained.

Figure 1 shows the schematic cross-section of the DFB structure with multiple quantum wells gratings for optical feedback. Two 4 nm-thick $In_{0.62}Ga_{0.35}As$ wells and 9.3 nm-thick InP barriers were first grown on InP substrate. First order gratings were delineated by holographic techniques and wet etching. After the regrowth of 65 nm-thick n-InP spacer layer, a standard strained-layer six-QW separate confinement heterostructure (SCH) was grown by CBE. The active QWs had 5 nm-thick $In_{0.6}Ga_{0.4}As$ wells and 18.6 nm-thick quaternary barriers with 1.25 μm bandgap energy, $Q_{1.25}$. The In composition in the QW grating was slighter higher than that of the active QW's for loss-coupled optical feedback. The thickness of $Q_{1.25}$ waveguide layers were 52.2 nm each. Buried heterostructure lasers were formed by employing regrowth of Fe-doped InP confinement layers using organometallic vapor phase epitaxy (OMVPE). Detailed growth and laser characteristics were reported elsewhere[16]. The 500 μm-wide laser was then mounted on a high frequency fixture for evaluations.

The schematic diagram of the test setup is shown in Fig. 2. A synchro-scan streak camera was used to record the time domain optical pulses, while the time-average spectra were monitored by an optical spectrum analyzer. Without microwave modulation, this gain-coupled DFB laser is lasing at single mode with a side-mode suppression ratio greater than 40 dB. Because the amount of absorption in the QW gratings can be controlled by the indium composition of the QW's as well as the thickness of the InP spacer layer and QW's, no self-pulsation were observed over the whole dc bias regime. This had been verified by sending the optical signal into a high speed detector mounted at the input of a highly sensitive microwave spectrum analyzer.

Figure 3(a) shows the time trace recorded by streak camera. The laser was biased at 60 mA ($4\times I_{th}$) and was driven by a microwave source at 4 GHz. It shows a 100 % optical modulation depth with a FWHM pulse width of 23 ps. The average output power is 6.7 mW and the peak power of the optical pulse is ~72 mW. The corresponding time-average spectrum is recorded in Fig. 3 (b). The optical spectrum shows a FWHM bandwidth of 0.14 nm which is corresponding to a time-bandwidth product of 0.405. This is very close to the transform-limited value of 0.31 for a hyperbolic secant pulse shape or 0.44 for a Gaussian shape.

3. MONOLITHIC CPM QUANTUM WELL LASERS

A colliding pulse mode-locked (CPM) scheme[17] is incorporated into the multiple quantum well laser to produce subpicosecond transform-limited pulses. Figure 4 shows the schematic diagram of this monolithic CPM quantum well laser grown by OMVPE.[18] The top contact stripe of the multiple quantum well laser is divided into five sections: a saturable absorber in the center, two modulator sections near the cleaved Fabry-Perot mirrors, and active waveguide sections linking the modulators and the absorber. Integrated microstrip transmission lines are used on the top of a semi-insulating iron-doped InP epitaxial regrowth layer to distribute the millimeter-wave synchronization signal to the two modulators in phase. The saturable absorber is reverse-biased, while the rest of the laser sections are forward-biased to provide gain.

We use the non-collinear second harmonic generation (SHG) auto-correlation technique to characterize these sub-picosecond pulses. Figure 5 shows the measurement setup for this mode-locking experiment. The measured SHG autocorrelation curve in Figure 6 fits very well by a hyperbolic secant square pulse shape with a pulse width as short as 950 femtoseconds. Near 100% optical modulation is obtained with very low RF power of 15dBm at 40 GHz for a 2.1 mm-long laser. From the 2.61nm (FHWM) spectral width of the mode-locked spectrum, the time-bandwidth product is 0.32, which is very closed to the theoretical limit of 0.314 for hyperbolic secant pulse shape. Because the waveguide is composed of the active medium, the mode-locking operation can be obtained over broad locking frequencies centered at half of the cavity round trip time, as shown in Figure 7. Without the synchronizing sources, free-running transform-limited pulses are generated by passive colliding pulse mode-lockinig[19]. The repetition rate is only determined by the 250-μm-long cavity length, and pulse width of 610 fs is obtained at a rate as high as 350 GHz, as shown in Figure 8.

4. SUMMARY

In summary, we have generated short optical pulses with nearly transform-limited time-bandwidth products by either gain switching or mode-locking of semiconductor lasers with monolithic cavities. These compact integrated high speed light sources are very useful for many applications in high bit-rate optoelectronic communication and computation systems.

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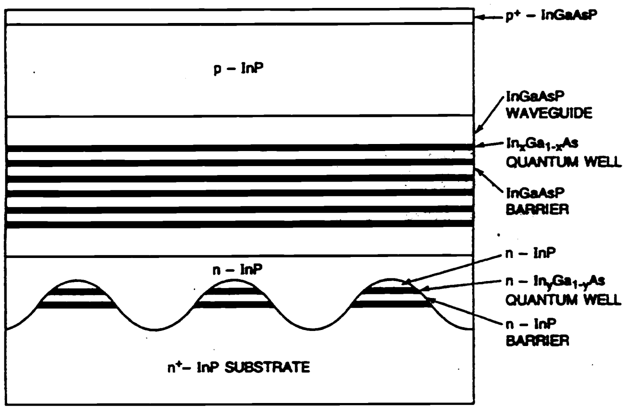

Fig. 1 Schematic diagram of the cross-section of a semiconductor gain-coupled distributed feedback laser with multiple quantum wells as the loss-gratings.

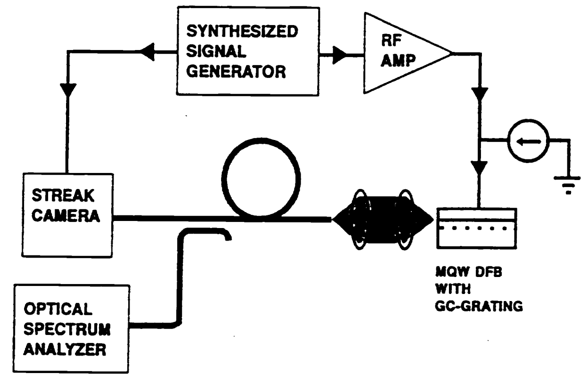

Fig. 2 The schematic diagram of test setups to measure the gain-switched lasers.

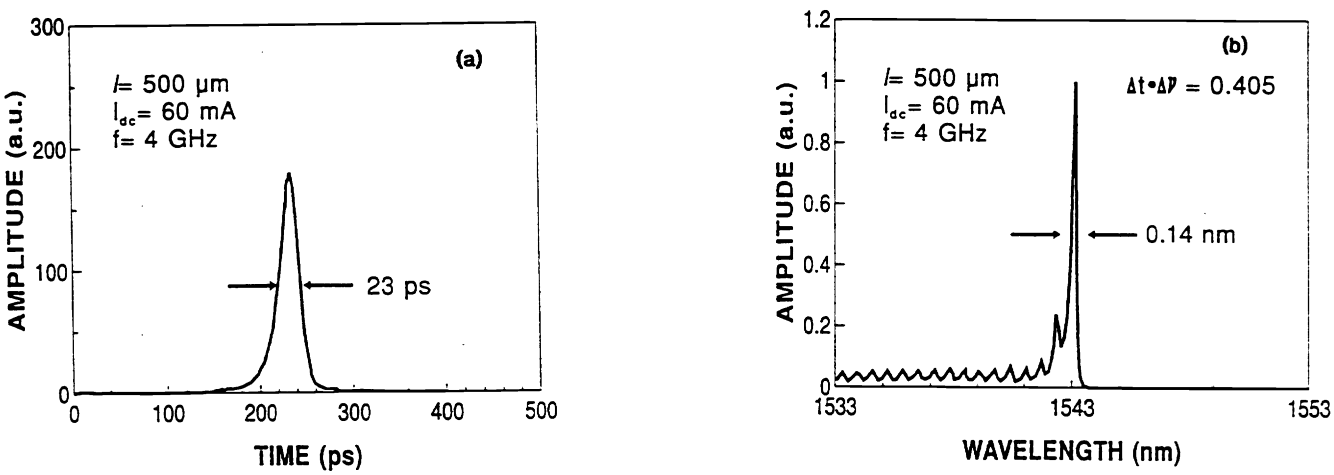

Fig. 3 (a) Measured streak camera trace of a gain-coupled DFB laser with MQW loss gratings. The laser is driven by a 4 GHz microwave oscillator, and the pulse width is 23 ps.

(b) The measured time-averaged spectrum corresponding to Fig. 3 (a). The FWHM bandwidth of 0.14 nm corresponds to a time-bandwidth product of 0.405.

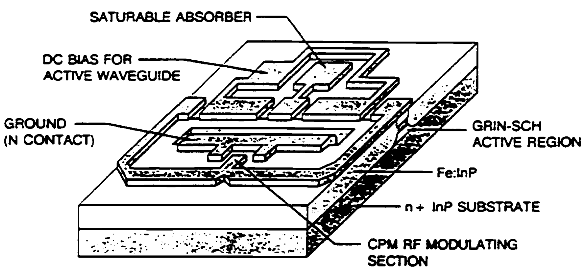

Fig. 4 Schematic diagram of a integrated colliding-pulse mode-locked quantum well laser on a single chip.

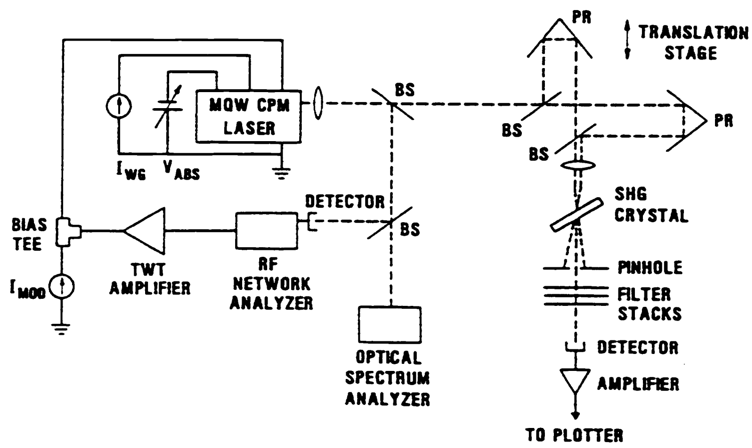

Fig. 5 Schematic diagram of the experimental setup to measure the pulse characteristics of monolithic CPM semiconductor lasers.

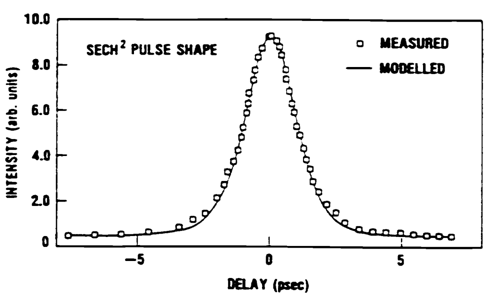

Fig. 6 Measured and modeled second harmonic autocorrelation trace of a CPM MQW laser at 40 GHz with a FWHM pulse width of 0.95 ps.

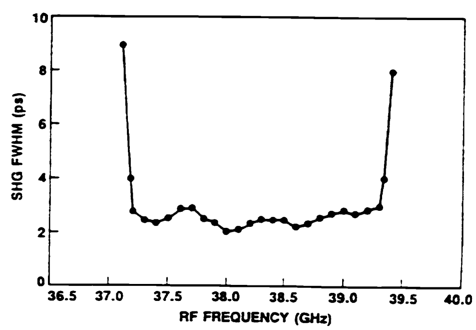

Fig. 7 Broad frequency tuning range of an active mode-locked CPM laser.

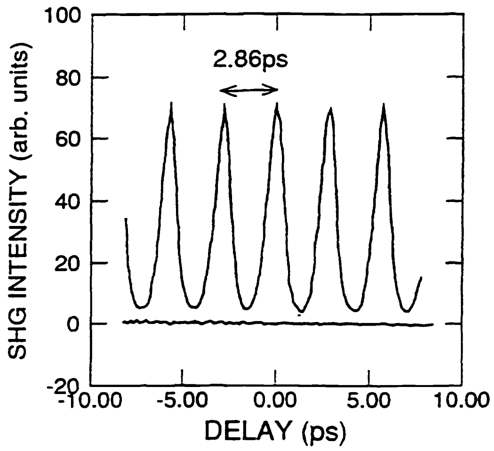

Fig. 8 Measured second harmonic generation autocorrelation trace of a passive CPM laser at 350 GHz. The pulse width is 610 fs and the cavity length of the laser is 250 um.