Review Article

Single-Section Fabry-Perot Mode-Locked Semiconductor Lasers

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We present a review of the theoretical models and experimental verification of the single-section Fabry-Perot mode-locked semiconductor lasers based on multiple-spatial-mode (MSM) coupling. The mode-locked operation at the repetition rates of 40 GHz and higher and the pulse width of a few picoseconds are confirmed by the intensity autocorrelation, the fast photo detection and RF spectrum, and the optical spectral interference measurement of ultrafast pulse. The spatial mode coupling theory of single-section Fabry-Perot mode-locked semiconductor lasers is also reviewed, and the results are compared with the experimental observations. The small signal modulation response of these lasers, which exhibits high-frequency responses well beyond the relaxation oscillation resonance limit, is also modeled theoretically, and the simulation is verified by the experimental measurements.

1. Introduction

Laser is a complex yet self-consistent system that is capable of demonstrating a wide range of dynamic behavior [1]. A simple and special case, where the laser operates in a single frequency continuous wave (cw) constant power operation, has found extensive application in many areas from data storage and retrieval to 3D holography. Mode-locked operation, where multiple longitudinal modes are lasing with time-invariant phase relationship, provides an important way of generating short optical pulse and ultra-stable high-frequency optical clock and also sees a wide range of applications including optical frequency comb generation [2] and nanostructure growth and patterning [3]. A more exotic operation regime, often referred to as the chaotic laser, is also a self-consistent solution of the complex dynamic system. Such novel lasers also start to find increasing interests [4]. These laser applications can almost always appreciate the good device/system features such as small footprint, electrical pumping, and simplicity in control [5]. For example, it was the invention of stable cw semiconductor lasers that made possible optical CD and DVD and optical communication. For the past 40 years, whereas we have almost mastered the art of making stable single-frequency semiconductor lasers through both

spatial mode and spectral controls [6–8], integrated mode-locked semiconductor lasers remain challenging [9, 10]. The fundamental difficulty comes from the fact that mode-locked operation typically requires action of saturable absorption in the laser cavity [1, 11, 12]. Integrated mode-locked semiconductor lasers seem to inevitably need at least two sections where one provides gain and the other saturable absorption [5, 9]. Such multisection semiconductor mode-locked lasers, however, are not easy to operate and control since delicate balance between bias currents of different sections is required for stable mode-locked operation [10]. In fact, such lasers typically can exhibit any of cw, mode-locked, and chaotic operations depending on the bias condition. Fabrication of multisection semiconductor mode-locked lasers is also challenging as one has to maintain between different sections good optical continuity while ensuring good electrical isolation. In this paper, we review a novel and simple mode-locked semiconductor laser design where there is only one section and therefore one bias current [13–18]. This type of compact Fabry-Perot mode-locked lasers has the advantage of low cost and high yield fabrication. Although against the intuition, the expected saturable absorption action is instead provided by spatial mode coupling in the active waveguide [14, 15]. When multiple spatial modes are allowed in the active waveguide and the field is amplified,

the light tends to concentrate more to the fundamental mode that sees the highest gain and the least loss. This change of light distribution among spatial modes favors higher intensity and results in an effective saturable absorption action. This effect is similar to the Kerr lens effect in the nonlinear gain media in free space [5], where the optical beam sees less clipping of the aperture and therefore less loss when the intensity is higher. The single-section Fabry-Perot mode-locked semiconductor laser operation has been previously observed in a wide range of wavelength and gain media [19–26]. Whereas the previous theoretical analysis based on the coupled rate equations of the longitudinal modes predicts that the mode-locked operation is a solution of the system, the rate equation system also supports other forms of solution such as mode competition, and the preference is not always clear [22, 23]. We presented an alternative time-domain model that shows the frequency-modulation (FM) mode locking, although a preferred solution does not self-start spontaneously [15]. The gap between the experimental observation of self-starting FM locking and the theory can be bridged by considering a multiple-spatial-mode (MSM) coupling system [15]. Furthermore, the MSM coupled system is also capable of generating amplitude-modulation (AM) mode-locked pulses directly without the need of external dispersive elements. The direct AM mode-locked operation from single-section Fabry-Perot semiconductor lasers has also been observed experimentally for a period of time in the quantum cascade lasers [24], the bulk and quantum well lasers [13, 14], and the quantum dash and quantum dot lasers [25, 26]. One shortcoming of these experimental observations is the lack of a direct proof of the time-invariant phase relationship between the lasing longitudinal modes. In this paper, we will also present the result of modulation spectral interference measurement [27] that directly verifies the time-invariant phase relationship.

This paper is arranged as follows. Section 2 reviews the structure and fabrication of the single-section semiconductor mode-locked lasers. Section 3 reviews the experimental confirmations of mode-locked operation by the optical spectra of the multiple lasing longitudinal modes, the intensity autocorrelation trace, the RF spectrum of fast optical-electrical (O/E) converted signal, and the modulation spectral interference method of pulse characterization. These thorough experimental studies firmly establish the mode-locked operation of such lasers. Then in Section 4 we summarize the simplified semiconductor laser model that is specifically applicable to the picoseconds semiconductor laser dynamics. The model applies to both single spatial mode and multiple spatial modes cases. Last but not least, in Section 5 we summarize the small signal modulation response of the MSM lasers and discuss the unique mechanism that contributes to the modulation responses that are beyond the relaxation oscillation resonance (ROR) limit.

2. The Device Structure and Fabrication

Figure 1 shows the schematics of the epilayer structure and the channel waveguide's cross section of the single-section Fabry-Perot mode-locked semiconductor laser with bulk or

FIGURE 1: The active waveguide structure of the single-section mode-locked semiconductor lasers. Distinctive to the layer structure are several passive lattice matched quaternary layers with graded composition. The active gain layer of multiple quantum wells (MQWs) can also be replaced by a bulk active layer.

TABLE 1: Base wafer epitaxial structure (LM: lattice matched).

#	Step	Thickness (nm)	Doping	Notes
0	n+-doped InP substrate		n+ 1e19	
1	InP buffer	500	UID	
2	Q1.1	115	UID	LM
3	Q1.2	115	UID	LM
4	Q1.3	122	UID	LM
5	InP ES	15	UID	
6	Q1.3	105	UID	LM
7	InP ES	15	UID	
8	Active (4QWs)	85	UID	bulk (<150), 6QW
9	InP clad	600	Graded Zn+ to 1e18	
10	Q1.3 cap	20	UID	LM
11	InP cap	20	UID	

quantum well gain [13, 14]. Compared to conventional index-guided semiconductor lasers, the current structure has several passive quaternary layers of graded composition in addition to the active epilayer that provides optical gain under current injection. In the figure, the lattice-matched quaternary layers are marked with their bandgap wavelength, for example, InGaAsP-1.3 μm represents the quaternary layer that is lattice matched to InP and has a bandgap wavelength at 1.3 μm. The figure shows the active epilayer to be that of multiple quantum wells (MQWs), although the similar structure also works with a single thin bulk gain layer. The base wafer epitaxial growth sequence is given in Table 1. All passive quaternary layers are lattice matched to the host InP. The channel waveguide core is formed by a deep wet etching processing step followed by standard n-i-n current blocking layer regrowth and a 2 μm p+ cap layer, which together bury the waveguide core. The p-metal contact is then formed directly on top of the waveguide channel. The width of the waveguide core is about 1 μm on the top. The deep wet etching forms a natural slope of the waveguide side

FIGURE 2: Three spatial modes supported by the channel waveguide structure given in Figure 1. The 2D boxes are $1.6 \mu\text{m}$ by $1.0 \mu\text{m}$. These modes have significantly different confinement factors to the gain layer and therefore modal gain and significantly different waveguide loss due to the roughness of the side wall. The mode effective indices are 3.62, 3.43, and 3.17, respectively.

wall. Due to different compositions of the quaternary layers, the side wall is less smooth than that of single homogeneous quaternary layer core waveguide. This additional roughness introduces more waveguide loss and at the same time also differentiates to greater extent the waveguide loss of different spatial modes. This larger differential modal loss benefits the MSM mode locking. Except for the difference in the base wafer's epilayer structure, the fabrication process of the single-section mode-locked semiconductor lasers closely resembles that of typical buried heterojunction (BHJ) laser diodes such as the ones in laser pointers and CD/DVD readers. In contrast to that of more sophisticated multiple section, monolithically integrated mode-locked semiconductor lasers, the simpler fabrication process ensures the needed high yield and low cost for production. Modal analysis shows that the given structure supports three spatial modes as shown in Figure 2. These spatial modes, besides having different effective propagation constants—therefore different sets of cavity resonant frequencies—also differentiate significantly in the modal gain and loss. In fact, the simulation

shows that the confinement factor to the gain layer, which can be calculated as a ratio between subdomain integrals, is different by a factor of four between the fundamental mode and the second order mode. The estimated waveguide loss coefficients due to the side wall roughness differentiate by a factor of more than five to the advantage of the fundamental mode. As we will see later in the paper, the theoretical modeling suggests that this large differential modal gain and loss favors the MSM mode locking. Figure 3 shows a scanning electron microscope (SEM) picture of the typical waveguide core of the single-section mode-locked semiconductor lasers. The side wall roughness due to the deep wet etching of different quaternary layers is clearly seen, especially at the active and passive quaternary layers' boundary. Whereas the larger waveguide loss tends to increase lasing threshold, the larger differential loss between the spatial modes is critical to the mode locking action. After the metal layer deposition, the lasers are cut to about 1 mm in length for 40 GHz operation. Both facets are cleaved as is and uncoated. The threshold current for such devices is typically below 20 mA. Coupling

FIGURE 3: The SEM picture of the waveguide core of a single-section mode-locked semiconductor laser. The corresponding layer composition is given in Figure 1. The roughness of the side wall, especially at the active and passive boundaries, is obvious. The large differential modal loss due to this side wall roughness is important to the multi-spatial-mode mode locking.

FIGURE 4: The typical L-I curve of a 1 mm long single-section mode-locked semiconductor laser. The output power detected here is the average power. The L-I curve is kink-free up to more than five times of the lasing threshold.

to single mode fiber is achieved by using an antireflection coated, tapered-fiber lens with the nominal focal length of $8\ \mu\text{m}$. Figure 4 shows a typical L-I curve. The lasing threshold is clear and sharp just below 20 mA. The L-I curve shown here is kink-free up to more than five times of the threshold. The kink-free L-I curve is good indication that there is no mode hopping in this type of lasers, which is consistent with the observed mode-locked operation.

3. The Mode-Locked Operation

The operation of the device is as simple as operating a laser pointer. Only one forward bias current is needed. For a wide range of the bias current basically from just above the lasing threshold to the maximal current that is limited by the thermal dissipation, the laser self-starts and remains

FIGURE 5: The optical spectra of a single-section mode-locked semiconductor laser at the various bias currents from just above the threshold (~ 20 mA) to 180 mA. The device under test here is a 0.9 mm long 4-MQW active layer device [13].

mode locked. Devices with 4-MQW [13], 6-MQW [14], and bulk gain layers are all tested, and all three types exhibit mode-locked operation. The repetition rate is determined by the length of the laser diodes. Fine tuning up to 1% can be achieved by current injection and/or thermal tuning. To confirm the mode locked operation, we use combined characterizations of optical spectra, intensity autocorrelation, radio frequency (RF) spectral measurements [13, 14], and a modulation-based spectral interference measurement of ultrafast pulses. Figure 5 shows the optical spectra of the laser output at various bias currents from 30 mA to 180 mA of a 4-MQW device [13]. The expansion of the lasing spectrum toward the longer wavelength side and the characteristic undulation of the spectral envelope are clear signatures of the self-phase modulation (SPM), which can be particularly strong for semiconductor materials with large linewidth enhancement factor (LEF) or the Henry factor. Figure 6 shows an intensity autocorrelation trace of the EDFA amplified pulse train of the same device [13]. We used a commercial intensity autocorrelator (FR-103MN, Femtochrom Research, Inc.), which employs crossed-beam geometry and a rotating pair of mirrors for rapid delay

FIGURE 6: The intensity autocorrelation trace shows a 47 GHz optical pulse train. The apparent difference in the pulse width of the consecutive pulses is an artifact inherent to the rotating mirror pair-based autocorrelators. The device under test is a 0.9 mm long 4-MQW active layer device [13].

FIGURE 7: The RF spectrum of the O/E converted laser output by a fast photo detector. The 3-dB linewidth is less than 1 MHz. The inset shows the full span spectrum. There is no spurious low-frequency spectral noise that is characteristic to irregular self-pulsation. The device under test here is a 1 mm long 6-MQW active layer device [14].

scanning. The apparent pulse width difference between the consecutive pulses in Figure 6 is an inherent artifact of the rotating mirror pair. The accurate measurement of pulse width is achievable in the middle region of the scanning range. This yields a pulse width of less than 5 ps, assuming a hyperbolic secant pulse shape. The large background level in the autocorrelation trace is contributed by the long tail of the pulses, which are not transform limited (see Figure 10). The intensity correlation alone is not sufficient to characterize the detail profile of the pulses.

The output of the lasers is also detected by a fast photo diode with response bandwidth of 50 GHz and the fast O/E converted signal is analyzed by an electrical spectrum analyzer [13, 14]. A typical narrow linewidth single RF tone is shown in Figure 7, which in this case is a 1 mm long 6-MQW device [14], exhibiting the super low noise operation of the mode-locked laser. The 3-dB linewidth of the RF tone

FIGURE 8: The experiment setup for modulation spectral interference measurement of ultrafast pulse. EOM: electro-optical modulator.

FIGURE 9: The spectra of the mode-locked optical pulse train modulated by a synchronized subharmonic tone. In this case, a 40.2 GHz optical pulse train is modulated by its 10.06 GHz subharmonic. The spectral intensity at the frequencies where the upper side bands and the lower side bands of neighboring longitudinal modes meet varies with the RF phase shifts imposed on the subharmonic tone only when the longitudinal modes have time-invariant phase relationship.

is less than 1 MHz. Inset in Figure 7 shows a full span RF spectrum from 300 kHz to 50 GHz. The instrument noise limited background except for the 40.2 GHz tone of the mode-locked repetition rate clearly indicates a clean mode-locked operation in contrast to other pulsing behaviors such as irregular self-pulsation. Multiple lasing longitudinal mode optical spectra and intensity autocorrelation traces are usually used to demonstrate mode locked operation. In some more careful studies, RF spectra of O/E converted pulse train signal are also used to confirm the regular timing of pulse arrival. Although these measurements are commonly accepted in the literature, questions can still remain for a direct proof that the multiple lasing longitudinal modes are indeed having a time-invariant phase relationship. In fact, the intensity autocorrelation trace can only confirm constantly arriving pulses or intensity spikes regardless the regularity of the arrival time. Whereas the RF spectrum can further confirm that the pulses are arriving at a regular timing, it does not ensure that the temporal profile remains stable from pulse to pulse. The stable pulse profile requires a time-invariant phase relationship between the lasing longitudinal modes, or by definition, the mode-locked operation.

FIGURE 10: (a) The pulse spectrum and the spectral phase. (b) The temporal profile and the temporal phase of the pulses.

To verify the time-invariant phase relation between the lasing longitudinal modes, we conducted the modulation-based spectral interference measurement that directly measures this fixed phase relation between the longitudinal modes inspired by [27]. The experimental setup for this measurement is shown in Figure 8. The input 40.2 GHz optical pulse train is split into two parts. The first part is optically amplified by an EDFA and then O/E converted and is used to recover a synchronized clock signal at 10.06 GHz by an RF 4:1 frequency divider. The recovered 10.06 GHz electronic clock signal is then amplified and fed through an RF tunable phase shifter that is capable of full 2π phase shift at 10.06 GHz. The phase shifted signal is then used to drive an electro-optical modulator (EOM) to modulate the second part of the input optical pulse train. The optical spectrum of the modulated signal is then recorded with various shifted phase. The upper (second) side band and the lower (second) side band of the neighboring longitudinal modes will coincide in frequency and interfere. If the longitudinal modes have a time-invariant phase relationship, the time averaged spectral intensity recorded by the optical spectrometer will vary with the shifted phase:

$$I\left(\omega_m + \frac{\Omega}{2}\right) = A_m^2 + A_{m+1}^2 + 2A_m A_{m+1} \cos(4\theta - \Delta\phi_m), \quad (1)$$

where Ω is the repetition rate of the pulse train. The A_m and A_{m+1} are the spectral amplitudes of the m th and the $(m+1)$ th lasing longitudinal modes, θ is the phase shift of the 10.06 GHz RF clock signal, and $\Delta\phi_m$ is the spectral phase difference between the m th and the $(m+1)$ th lasing longitudinal modes. Part of raw recorded interfered spectra is shown in Figure 9 for various phase shifts. In middle positions between neighboring lasing longitudinal modes, spectral intensity changes with the phase shifts of the 10.06 GHz modulating signal. This is clear and unequivocal indication that the lasing longitudinal modes have a time-invariant phase relationship, or, by definition, the laser is mode locked. A phase retrieval algorithm can recover the spectral phase profile of the optical pulses, and the result is shown in Figure 10. The laser under the test here is a 6-MQW active layer sample operating at a bias current of 154 mA. The measured time profile using this method is in good agreement with the previous autocorrelation measurements. Details of the modulation-based spectral interference measurements of single-section mode-locked semiconductor lasers and the phase retrieval algorithms will be discussed elsewhere. The mode-locked operation is highly robust and repeatable, and it has been observed in the devices with different active layer structures including bulk active, 4-MQWs [13], and 6-MQWs [14]. Measurement results for various bias current values are summarized in

TABLE 2: Pulse measurement results for various bias current values.

Bias current (mA)	Pulse width (ps)	Chirp parameter β
155	4.62	-2.85
165	4.63	-2.25
175	4.77	-2.92
185	4.81	-2.32
195	4.67	-1.77
205	4.68	-2.42
215	4.62	-1.88

Table 2. For smaller bias current values, the clock recovery circuit is having difficulty to trigger a clean enough signal for the measurement. The chirp parameter β characterizes the frequency chirp with the instantaneous frequency $\omega(t) = \beta(t - t_0)/\tau$, where τ is the pulse width in time and t_0 is the pulse center [12]. Experimentally, β can be estimated using $|\beta| = (\tau/\tau_0 - 1)^{1/2}$ from the measurement data by comparing the pulse width τ with the transform-limited pulse width τ_0 assuming a flat spectral phase dependence. The sign of β is determined from the spectral phase profile recovered. Table 2 results show that both pulse width and chirp parameter vary in a small range, which is consistent with the theory for small chirp parameter values. The negative sign of β implies that the frequency chirp is red-shifting in time, which is also consistent with the theory.

4. The Theoretical Model

The extensive experimental studies summarized in the previous section have established unequivocally that these single-section semiconductor lasers are mode locking. However, there are no identifiable saturable absorbers involved. This is at odds with traditional self-starting, passive mode locking models [11, 12]. In this section, we review the coupled spatial mode theory [15] that in one stable operation regime supports mode-locked operation. For laser dynamics on the time scale in picoseconds, one can write for single section, single-spatial-mode lasers [15],

$$\left[-l + i\theta + g(1 + i\alpha) \left(1 + \frac{1}{\Omega_g^2} \frac{d^2}{dt^2} - \frac{|a|^2}{P_{sf}} \right) + iD \frac{d^2}{dt^2} \right] a = 0. \quad (2)$$

The entity enclosed in the square bracket can be recognized as the round trip differential operator, where a is the amplitude of the light field, l is the round-trip cavity loss coefficient, θ is the roundtrip propagation phase.

$$g = \frac{g_0}{(1 + |a|^2/P_s)} \quad (3)$$

is the average-power saturated gain coefficient, where g_0 is the small signal gain and P_s is the saturation power due to the slow carrier dynamics in the semiconductor. $|a|^2$ denotes time averaged power. Also in (2), α is the Henry factor (LEF); Ω_g is the gain bandwidth, P_{sf} is the saturation power due to the fast carrier dynamics in the semiconductor [15], and D is

the group velocity dispersion (GVD) parameter. The real part of the master Equation (2) governs the balance between gain and loss,

$$-l + g \left(1 - \frac{A^2}{P_{sf}} \right) + \frac{g}{\Omega^2} \left(\ddot{A} - \dot{\phi}^2 \right) + \left(\frac{g\alpha}{\Omega^2} + D \right) \times \left(2\dot{\phi} \frac{\dot{A}}{A} + \ddot{\phi} \right) = 0, \quad (4)$$

where the first term is the loss and the rest terms are the solution dependent gain. Here $a = A \exp(-i\phi)$, and $\dot{A}, \dot{\phi}$ are the first order derivatives of A and ϕ respect to time, and $\ddot{A}, \ddot{\phi}$ are the second order derivatives. Given the cavity loss coefficient l , the solution that supports the highest gain will win. The governing Equation (4) therefore suppresses any power variation due to the second and third terms in (4). Accordingly, single section, single-spatial-mode lasers only prefer constant power operation. Furthermore, such lasers, in the presence of nonzero GVD and/or amplitude-phase coupling (due to the Henry factor α), prefer solutions with nonzero $\ddot{\phi}$. Random $\ddot{\phi}$ leads to mode partition noise. On the other hand, deterministic nonzero $\ddot{\phi}$ leads to FM mode-locking operation [15]. Whereas the FM mode-locking operation can be a preferred solution [19–23], unlike AM mode locked cases with saturable absorbers, this special solution with constant power and heavy chirp does not arise from noise naturally. Consequently, single-section, single-spatial-mode lasers do not self-FM mode lock. The self-starting FM mode-locked operation is an effect of multiple-spatial-mode coupling [15].

When the laser cavity supports multiple spatial modes, each spatial mode obeys a dynamic equation similar to (4). Whereas these spatial modes are orthogonal to each other in the cavity without pumping, or the “cold cavity” for short, the pumping usually perturbs the index profile of the waveguides. This perturbation couples the spatial modes and the system is now described by a set of simultaneous coupled differential equations,

$$\hat{o}_m a_m + \sum_n \kappa_{mn} (1 + i\alpha) \left(1 - \frac{|a|^2}{P_{sf}} \right) a_n = 0, \quad (5)$$

where $|a|^2 = \sum |a_m|^2$ $\hat{o}_m$ is the round trip differential operator for the m -th mode,

$$\hat{o}_m = -l_m + i\theta_m + g_m(1 + i\alpha) \times \left(1 + \frac{1}{\Omega_g^2} \frac{d^2}{dt^2} - \frac{\sum |a_m|^2}{P_{sf}} \right) + iD_m \frac{d^2}{dt^2}, \quad (6)$$

and κ_{mn} is the coupling coefficient between the m th and n th modes. For a gain coupled “hot cavity” (pumped cavity), for example, one can write

$$\kappa_{mn} = \int u_m^*(r) g(r) u_n(r) dr, \quad (7)$$

where $u_m(r)$ is the mode's field profile of the m th unperturbed cavity spatial mode over the lateral dimensions

r and $g(r)$ is the spatial dependent gain due to, for example, nonuniform current distribution and/or spatial hole burning due to MSM. The dynamic system prescribed by (5) is a nonlinear coupled differential system. Such system is capable of generating very complex dynamic behaviors including chaos. Critical parameters such as coupling coefficients in this case can be designed and, therefore, controlled experimentally. Accordingly, the single-section MSM semiconductor lasers can serve as a theoretical and experimental paradigm for controlled complex dynamics. One special and orderly behavior is the mode-locked operation. This can be illustrated by considering a much simplified case where only two spatial modes are involved and the fundamental mode dominates the higher-order mode in power. In this case, one can have for the dominate fundamental mode,

$$\left[-l + i\theta + g \left(1 + \frac{1}{\Omega_g^2} \frac{d^2}{dt^2} \right) + iD \frac{d^2}{dt^2} + (\gamma - i\delta) |\tilde{a}|^2 \right] \tilde{a} = 0, \quad (8)$$

where $\tilde{a} = a_1/\sqrt{P_{sf}}$ is the scaled field amplitude normalized to the square root of the fast saturation power. l, θ, g, Ω_g , and D are still the round trip loss coefficient, the round trip propagation phase, the DC power saturated gain, and the gain bandwidth and the GVD parameter for the fundamental mode and the subscript "1" is dropped for brevity. The newly acquired nonlinear terms are characterized by the effective self-amplitude modulation (SAM) parameter γ and the effective SPM parameter δ :

$$\begin{aligned} \gamma &= \frac{g(\alpha^2 - 1 - \eta)}{\eta}, \\ \delta &= \frac{g\alpha(2 + \eta)}{\eta}, \end{aligned} \quad (9)$$

where $\eta = gl_2/|\kappa|^2$ characterized the strength of the coupling. l_2 is the round trip loss coefficient of the higher-order mode and $|\kappa|^2$ is the strength of the spatial mode coupling. Equation (8) can be recognized as the additive pulse mode-locking (APM) master equation [11, 12]. When the SAM parameter γ is positive, the laser system governed by (8) is capable of self-start mode locking as it is equivalent to a fast saturable absorber [11]. When coupling is strong (η is small), the energy among different modes can be more easily redistributed. As mentioned in the introduction, the change of light distribution among spatial modes in active waveguides favors higher intensity as the light tends to concentrate more to the fundamental mode that sees the highest gain and the least loss. This leads to the needed effective saturable absorption action. Both the spatial mode coupling and the Henry factor LEF, which couples amplitude modulation with phase modulation, are critical for self-start mode locking in such lasers. If Henry factor α^2 is smaller than $1 + \eta$, for example, the system will not favor any pulsed operation and will prefer a constant power output. Figure 11 shows the dependence of the SAM parameter to the spatial mode coupling for different values of the Henry factor. In order to achieve the mode-locked operation,

FIGURE 11: The dependence of SAM parameter on the spatial mode coupling and the AM-PM coupling. Positive SAM parameter describes saturable absorption action and supports self-start mode locking. The vertical axis is the dimensionless effective SAM parameter γ/g .

strong spatial mode coupling and amplitude-modulation-phase-modulation (AM-PM) coupling (i.e., a large Henry factor) are preferred. The solution to (8) is a chirped hyperbolic secant pulse. The pulse chirp parameter β can be analytically calculated, and it depends on both SAM and SPM parameters. Figure 12 shows this chirp parameter and its dependence on both spatial mode coupling and AM-PM coupling. While a larger α leads to a bigger range for mode-locked operation in terms of the spatial mode coupling strength, the output ultrafast pulses are also more heavily chirped. The ideal hyperbolic secant pulse profile assumes a parabolic gain profile. In reality, the gain profile can be asymmetric and the heavily chirped pulses in real systems can also exhibit asymmetric pulse profile in time as seen in the experimental measurement results shown in Figure 10.

The above coupled spatial mode theory shows and explains how single-section semiconductor lasers can operate in the regime of a self-start and stable mode-locked operation. The predictions of design parameters for the mode-locked operation and pulse characteristics agree very well with the experimental observations.

5. The Modulation Properties of Single-Section MSM Semiconductor Lasers

Single-section MSM lasers can be considered as multiple lasers share a common cavity. The spatial mode coupling discussed in the previous section is also the mechanism by which these lasers couple. Coupled lasers, on the other hand, not only can be mode locked, their direct modulation response is also characteristically different from that of individual uncoupled lasers. The small signal modulation response, for example, is not limited by the ROR limit, which is the main bandwidth limiting factor for direct modulation of lasers. The single-section MSM lasers, therefore, should

FIGURE 12: The pulse chirp parameter of the output pulses from mode-locked lasers governed by the master Equation (8). Strong couplings, while more supportive to mode locking, tend to result in large pulse chirp.

also have extraordinary modulation response. While ROR limit roots in the coupling of cavity photon energy to the outside of the cavity, multiple spatial modes allowed in the cavity provide many additional channels for the photon energy to couple between different spatial modes. As a result, the modulation response of MSM lasers is not limited by the ROR limit. In this section, we first summarize the small signal modulation analysis of this type of lasers using MSM coupled rate equations. Then we compare the simulation with the experimental data.

The MSM coupled rate equations for the special case of two spatial modes that was considered in the previous section are

$$\begin{aligned} \frac{dN}{dt} &= \frac{J}{ed} - \frac{N}{\tau_s} - A_1(N - N_{t1})P_1 - A_2(N - N_{t2})P_2, \\ \frac{dP_1}{dt} &= A_1(N - N_{t1})P_1 - \frac{P_1}{\tau_1} + \kappa P_2, \\ \frac{dP_2}{dt} &= A_2(N - N_{t2})P_2 - \frac{P_2}{\tau_2} + \kappa P_1, \end{aligned} \quad (10)$$

where τ_1 and τ_2 denote the photon lifetimes for the first and second spatial modes, respectively. Similarly, P , N_t , and A with the indices of 1 and 2 denote the photon density, the threshold carrier concentration, and the differential quantum efficiency for the first and second spatial modes. κ characterizes the coupling between the spatial modes. For (10), it is assumed that $P_1 \gg P_2$ as appropriate for the mode-locked case. Since each spatial mode has its own effective propagation constant, different spatial modes have different sets of longitudinal resonant frequencies. The two frequency combs have different mode (frequency) spacings due to different effective propagation constants for the spatial modes. The intermixed tones between the two frequency combs provide a rich spectrum, which, when the spatial modes are coupled, yields a rich spectrum for the coupling coefficient. This is analogous to the acoustic effect that, when two notes are struck simultaneously on a piano, the beating of the notes has a rich (sound) spectrum due to the intermixed tones between the harmonics of the notes. In fact, this effect is a basis for the acoustic tuning of a piano. For MSM lasers, due to the same “piano-tuning” effect, the spatial mode coupling κ in (10) has a rich spectral response.

Linearization of (10) around a steady-state operation point $(J_0, N_0, P_{10}, P_{20})$ yields, for $J = J_0 + \Delta J$, $N = N_0 + \Delta N$, $P_1 = P_{10} + \Delta P_1$, and $P_2 = P_{20} + \Delta P_2$,

$$\begin{aligned} \frac{d\Delta N}{dt} &= \frac{\Delta J}{ed} - \left(\frac{1}{\tau_s} + A_1 P_1 \right) \Delta N - \frac{\Delta P_1}{\tau_1} - A_2 (N_0 - N_{t2}) \Delta P_2, \\ \frac{d\Delta P_1}{dt} &= A_1 P_1 \Delta N + \kappa \Delta P_2, \\ \frac{d\Delta P_2}{dt} &= A_2 P_2 \Delta N - \frac{\Delta P_2}{\tau_2}. \end{aligned} \quad (11)$$

Again, here we have used $P_1 \gg P_2$. For the steady-state operation point where the fundamental mode is lasing beyond the threshold, one has approximately $A_1(N - N_{t1}) \approx 1/\tau_1$ [17]. For the higher order mode, which is also supported by the cold cavity, the absorption is much larger in comparison with that of the fundamental order mode. Accordingly, $A_2(N_{t2} - N_0)P_2 \approx \kappa P_1$. Solving (11) for the modulation response $\Delta P_1/\Delta J$, one has

$$\frac{\Delta P_1}{\Delta J} \approx \frac{A_1 P_1 / ed + A_2 P_2 \tau_2 \kappa(\omega) / ed}{A_1 P_1 / \tau_1 - \omega^2 + j\omega((1/\tau_s) + A_1 P_1) + (A_2 P_2 / \tau_1)[\kappa(\omega)\tau_2 - j\omega A_2(N_{t2} - N_0)\tau_1\tau_2]}, \quad (12)$$

where $\kappa(\omega)$ is significant only when the modulation frequency is close to an intermixed tone of beating frequencies between the spatial modes. Consequently, for a smaller ω that is close to the ROR frequency $\omega_{\text{RO}} = (A_1 P_1 / \tau_1)^{1/2}$, $\kappa(\omega)$ is usually small and does not change appreciably the ROR response. When ω is getting closer to beating resonances

of $\kappa(\omega)$, on the other hand, the modulation response starts to deviate significantly from the single spatial mode case. Figure 13 shows a simulated modulation response together with the experimental measurement results. The theoretical curve (dashed curve in the figure) assumes that a Lorentzian resonance profile for $\kappa(\omega)$ at a beating frequency of 8 GHz.

FIGURE 13: Small signal modulation response of an MSM mode-locked laser. Dashed curve is the theoretical model presented here. Solid curves are the measured modulation responses for bias currents varied from 40 mA to 170 mA.

$\kappa(\omega)$ in general has a much richer beating resonant structure that can be determined by the “piano-tuning” effect of spatial modes discussed previously. The resulting modulation response shows two resonance peaks. The one at 2 GHz range is related to the cavity photon lifetime, which would be the case in a conventional single-section laser corresponding to the ROR peak. The second resonance peak at 8 GHz is due to the MSM coupling $\kappa(\omega)$, which has a beating frequency of 8 GHz. The experimental results are of the modulation responses of a single-section MSM mode-locked laser that is packaged in a butterfly package. The high-frequency RF feed-through type of packaging was unavailable at the time of testing. Consequently, the experimental responses fall off at higher frequencies due to the bandwidth limited packaging. Nonetheless, the presented theory with the simple beating resonant structure between spatial modes agrees well with the experimental measurement. The theoretical model also demonstrates that the MSM beating resonances are not limited by the ROR limit. While the current direct modulation bandwidth of QW lasers can exceed 20 to 30 GHz when biased at very high pump currents, it is still very encouraging that the broadband/high-frequency direct modulation without the ROR limit is possible at a much higher frequency for this type of single-section MSM semiconductor lasers.

6. Discussion and Conclusions

Typically mode-locked lasers need a pulse compressing mechanism to compensate for the gain medium that usually broadens the pulse. Intuitively in MSM mode locking scheme presented here, the pulse compressing action comes from the saturable absorption effect, where the higher intensity sees a smaller loss. The spatial mode coupling is compounded with the fast gain saturation process and leads to the nonlinear action of saturable absorber. Based on the APM principles

[11, 12], the dynamic Equation (8) gives rise to mode locking action when SAM parameter γ is positive. According to the theory presented, the gain media need to have a large enough LEF to facilitate the mode locking for a given level of the mode coupling. LEF is typically much smaller in solid-state lasers and gas lasers compared to semiconductor lasers and needs a stronger mode coupling to facilitate this type of mode locking. While the MSM mode-locked lasers involve multiple spatial modes at operation, only the fundamental mode has the dominant power. Accordingly, the beam quality is not significantly affected.

In conclusion, we reviewed the experimental results and theoretical model for the single-section MSM mode-locked lasers. Our experimental studies established unequivocally that these single-section semiconductor lasers are self-starting mode-locked lasers. This provides a potentially low cost and high yield method for commercialization of mode-locked laser diodes. The theoretical investigation of these lasers points out the root of the mode locking mechanism to be the MSM coupling. These single-section mode-locked semiconductor lasers, in contrast to other types of compact mode-locked lasers such as the multi-contact integrated semiconductor mode-locked lasers, have the advantages of simple fabrication, wide range of stable mode-locked operation, and single bias and control. The direct modulation response of these MSM lasers is also modeled and measured. Due to the MSM’s “piano-tuning” effect, the direct modulation response of MSM lasers is not limited by the ROR limit and can potentially extend to 100 GHz and beyond.

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