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Ultrashort pulse generation in a semiconductor laser with strong coherent optical feedback

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Abstract: In this paper, we propose a novel technique for generating ultrashort pulses using a semiconductor laser subject to strong optical feedback from short external cavities. The influence of three system parameters, viz the external cavity length, the injection current and the feedback strength on the characteristics of the ultrashort pulses are numerically investigated. The results show that the pulse width decreases and the pulse peak increases with increase of any of these three parameters. The repetition frequency of the ultrashort pulses decreases with increase of the feedback strength but increases with increase of the injection current. Based on these results, ultrashort pulses with a pulse width of 3.6 *ps* and a repetition frequency of 2.3 *GHz* have been achieved when the injection current is four times the threshold current. The pulse width can be further decreased and the repetition frequency can be further increased by appropriately adjusting the external cavity length and feedback strength. The results presented in this paper open up a new route for designing ultrashort pulse generators for incorporation in future photonic integrated optical circuits.

1. Introduction

Semiconductor laser sources of ultrashort optical pulses are needed in optical communications systems as pulse sources for high speed data transmission and all-optical signal processing [1]. To produce such sources, several techniques have been explored, such as gain switching [2-7] and different types of mode locking [8-15].

In this paper, a novel technique is proposed to generate ultrashort pulses using a semiconductor laser (SL) with external optical feedback (EOF). Comparing to other techniques, an SL with EOF requires neither external modulation nor saturable absorbers and the pulses generated have a single centre wavelength which are important in several applications, such as dense wavelength-division multiplex (DWDM) communications [16] and multi-photon imaging for clinical diagnostics [17]. With the aid of rate equations, we identify a region where the ultrashort pulses are generated by exploring basic parameters of the SL with EOF, and specifically the laser injection current, the external cavity length and the feedback strength. Attention is then given to the influence of these parameters on the characteristics of the ultrashort pulses. Finally, we draw our conclusions and the feasibility of the proposed scheme is briefly discussed.

It should be noted that the pulses discussed in this letter are different from those in [18-22] which are also generated using an SL with EOF. In this paper, pulses refer to emissions of light characterized by a fixed duration and repetition frequency. In contrast, in [18-22], the pulses are harmonic oscillations of a continuous light intensity which corresponds to period one oscillations of the SL with EOF [23]. These two types of pulses have their own advantages and applications in other contexts.

2. Theory

The behaviour of single mode semiconductor lasers with coherent external optical feedback can be described using the following equations which are based on the well-known Lang and Kobayashi (L-K) equations [24, 25]. Note that the L-K equations can also be modified to describe single mode semiconductor lasers with incoherent feedback which model has been used and tested for many years to study the generation of single wavelength picosecond pulses [16, 26, 27].

$$\frac{dS(t)}{dt} = \frac{1}{2}\left\{G_N\left[N(t)-N_0\right]-\frac{1}{\tau_p}\right\}S(t) + \sum_{q=1}^{M}\frac{\kappa_q}{\tau_{in}}\cdot\sqrt{S(t)S(t-q\tau_{ext})}\cdot\cos\left[q\omega_0\tau_{ext}+\phi(t)-\phi(t-q\tau_{ext})\right] \quad (1)$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha\left\{G_N\left[N(t)-N_0\right]-\frac{1}{\tau_p}\right\} - \sum_{q=1}^{M}\frac{\kappa_q}{\tau_{in}}\cdot\frac{\sqrt{S(t-q\tau_{ext})}}{\sqrt{S(t)}}\cdot\sin\left[q\omega_0\tau_{ext}+\phi(t)-\phi(t-q\tau_{ext})\right] \quad (2)$$

$$\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - G_N\left[N(t)-N_0\right]S(t) \quad (3)$$

where t is the time, $S(t)$ is the photon density, $\phi(t)$ is the phase and $N(t)$ is the carrier density. Multiple reflections of light are included in (1)-(2) [25], where M and q are integers which represent the total number of round-trips and q-th round-trip of light in the external cavity respectively. τ_{in} is the laser internal cavity roundtrip time. ω_0 is the optical angular frequency of the solitary laser. Note that $\omega_0=2\pi c/\lambda_0$, where c is the speed of light in vacuum and λ_0 is the laser wavelength. α is the linewidth enhancement factor [28]. The three main controllable parameters for the SL with EOF are, respectively, feedback power coupling factor κ_q, the injection current J and the laser external cavity roundtrip time τ_{ext}. κ_q is expressed as:

$$\kappa_q = \frac{r^2-1}{r^2}(-rr_{ext})^q \quad (4)$$

where r and r_{ext} are the amplitude reflectivity of laser facet and external mirror. $J=J_R J_{th}$ where J_R is the ratio between J and the threshold current J_{th}. $J_{th}=(N_0+G_N^{-1}\tau_p^{-1})\tau_s^{-1}$ where N_0 is the carrier density at transparency, G_N is the gain coefficient, τ_p and τ_s are respectively the photon lifetime and carrier lifetime. $\tau_{ext}=2L_{ext}/c$, where L_{ext} is the external cavity length. The detailed derivation of (1)-(3) can be found in [25, 29, 30] where the main assumption is the neglect of spatial variation of the carrier density within the active region.

A fourth order Runge-Kutta method was used to numerically integrate equations (1)-(3) where a temporal resolution of $\Delta t=50$ *fs* is used and the duration of the time series is 0.1 μs. J_R, L_{ext} and r_{ext} are three variables used to investigate the region where the pulses are generated and the characteristics of the pulses. All other parameters are fixed as follows: $\omega_0=1.2\times10^{15}$ $rad\cdot s^{-1}$ ($\lambda_0=1550$ nm), $c=3.0\times10^8$ $m\cdot s^{-1}$, $\alpha=6.0$, $N_0=1.1\times10^{24}$ m^{-3}, $G_N=8.1\times10^{-13}$ $m^3\cdot s^{-1}$, $\tau_p=2.0\times10^{-12}$ s, $\tau_s=2.0\times10^{-9}$ s, $r=0.3$, $\tau_{in}=8.0\times10^{-12}$ s. In general, when M is greater than 10, the simulation results are unchanged due to the weakness of the higher order reflected light. For example, for $r_{ext}=0.9$, when q reaches 10, the feedback coupled power is only 5.6×10^{-4} % of the emitted power according to (4). Therefore, M is set as 12 in the simulations.

To generate ultrashort pulses, a short external cavity and strong feedback are considered in this paper. Here, a short external cavity is conventionally defined as when the external cavity frequency (f_{ext}) is larger than the relaxation oscillation frequency (f_{RO}) of the stand-alone laser. Strong feedback corresponds to cases where the amplitude reflection of the external mirror is >80%. Under these conditions, when the laser turns on and undergoes the first cycle of the relaxation oscillation, the successively reflected light due to multiple reflections is strong enough to deplete the gain below the threshold, thus making the laser temporarily turn off. However, due to the continuous bias current injection, the gain will again increase to the level above the threshold after a short time that depends on the carrier lifetime [31], and the laser will turn on again and then repeat the previous process to generate a train of identical ultrashort pulses. Therefore, in contrast to other traditional methods used for locking the phases of the modes, the mechanism of our proposed method is the gain depletion in the laser induced by optical feedback which leads to the simplicity of the proposed approach.

Based on such a mechanism, tailoring pulse properties such as the pulse width, pulse repetition frequency and pulse power may be expected using the following means:

1. *Fine tuning the external cavity length within a range where the light phase can be continuously tuned over 2π.* In this way, the phase of the reflected light can approach that of the emitted light so that the laser tends to be mode-locked with a consequent increase in the pulse peak power and decrease in the pulse width. However, it should be appreciated that this effect will also increase the turn-on delay time of the laser leading to a reduced pulse repetition frequency. Therefore, in this case, there is a trade-off between pulse width and repetition frequency requiring careful choice of the external cavity length.

2. *Variation of the laser bias current.* With increased bias current, the laser output power and its relaxation oscillation frequency increase. In turn the rate of gain depletion will also increase leading to shorter optical pulses. Higher injection current also leads to a shorter laser turn-on delay time (T) [31], and hence the pulse repetition frequency (1/T) would be expected to increase with increase of injection current. As the laser output power increases with the injection current, the pulse peak power would also be expected to increase with increase of the injection current.

3. *Variation of the feedback strength*. In this case, an increase occurs in the reflected light thereby enhancing the gain depletion and thus shortening the pulse width. Similarly, the pulse peak power would be expected to increase. However, as in the case of cavity length variation, a faster gain depletion will also increase the laser turn-on delay thereby impacting the pulse repetition frequency. Therefore, careful choice should also be made of the feedback strength to achieve the required pulse widths and repetition frequencies.

3. Results

With the aim to explore the generation of ultrashort pulses based on the above mechanism, in the simulations, $r_{ext}=0.90$ and J_R takes 100 values equally spaced within the range of $J_R \in [2, 4]$ which corresponds to $f_{RO} \in [4.19$ GHz, 5.94 $GHz]$ via $f_{RO}=(2\pi)^{-1}[(J_R-1)(1+G_N N_0\tau_p)(\tau_p\tau_s)^{-1}]^{1/2}$ [32]. L_{ext} takes 5000 values equally spaced within the range of $L_{ext} \in$ [100 μm, 150 μm]. Within such a range of L_{ext}, 5000 values make L_{ext} vary with a step size of 10 nm which corresponds to $0.013\lambda_0/2$ and a change of light phase of 0.026π. Also, the external cavity lengths are very short where $f_{ext}=c/(2L_{ext}) \in$ [1.0 THz, 1.5 THz] which is much higher than f_{RO}. Figure 1 maps the ultrashort pulses areas in terms of J_R and L_{ext}. In Fig. 1, the blue dots represent where the ultrashort pulses are generated. An enlarged view of the red dashed box in the main figure is shown in the inset (I). The blue dash areas indicate the laser exhibiting ultrashort pulses dynamics. The green dashed box in the inset (I) is further enlarged, shown in the inset (II) of Fig. 1.

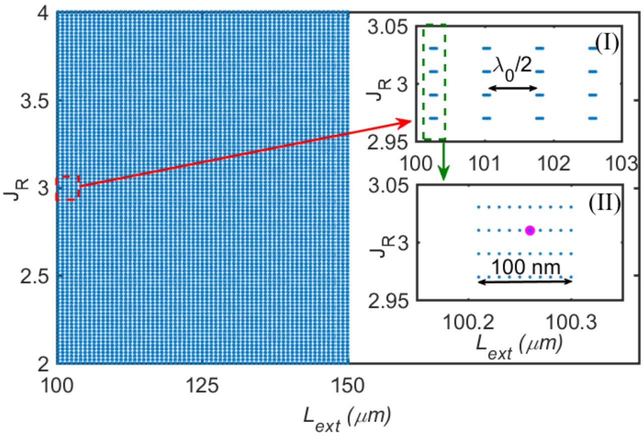

Fig. 1. *A map showing where the ultrashort pulses are generated in terms of J_R and L_{ext} when $r_{ext}=0.90$. Blue dots represent where the ultrashort pulses are generated. Insets: (I) an enlarged view in the red dashed box showing the pulses are generated with every change of $\lambda_0/2$ in L_{ext}, (II) an enlarged view of the green dashed box in the inset (I) showing the tunable range for generating pulses is 100 nm.*

From Fig. 1, it can be seen that, for all the values of J_R, ultrashort pulses are generated periodically with a period of $\lambda_0/2$ (as shown in inset (I) of Fig. 1). Within a period of $\lambda_0/2$, the range of ΔL_{ext} with ultrashort pulses is 100 nm as shown in inset (II) of Fig. 1. Within these ranges, it is anticipated that the phase of the emitted light is close to or matches that of the reflected light where constructive interference occurs, and the laser is self-mode-locked. Note that, such a range also corresponds to a phase change ($\Delta\phi$) of about $\pi/4$ where $\Delta\phi=4\pi\Delta L_{ext}/\lambda_0$. Therefore, the pulse formation process of the proposed approach is robust to some variations to the phase consequent to fluctuations of injection current or temperature.

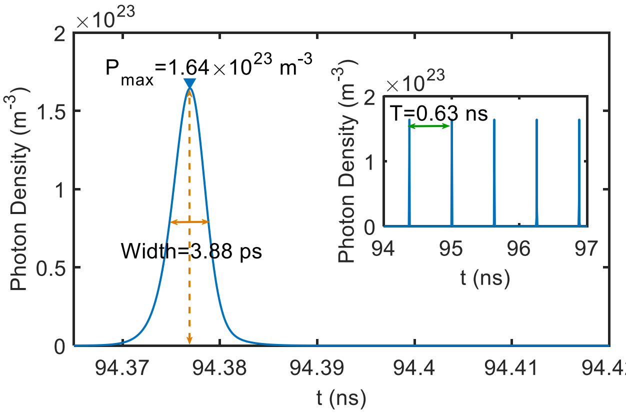

Fig. 2. *An ultrashort pulse extracted from a simulated train of pulses shown in the Inset, where L_{ext}=100.26 μm, J_R=3.01 and r_{ext}=0.90, as indicated by the pink dot in Fig. 1.*

Figure 2 shows an ultrashort pulse extracted from a simulated train of ultrashort pulses (inset of Fig. 2), where L_{ext}=100.26 *μm*, J_R=3.01 and r_{ext}=0.9, which corresponds to the pink dot shown in inset (II) of Fig. 1. As depicted in Fig. 2, there are three parameters to characterize the ultrashort pulses. They are respectively the pulse width (FWHM), the repetition frequency (1/T) and the pulse peak (P_{max}). From Fig. 2, it can be seen that the pulses generated in the SL with EOF are high-speed (repetition frequency is 1.59 *GHz*) ultrashort (pulse width is 3.88 *ps*) pulses with a pulse peak of 1.64×10^{23} m^{-3}. Note that such a pulse peak is two orders of magnitude larger than the photon density (1.35×10^{21} m^{-3}) of the laser in continuous wave (CW) operation where L_{ext}=100.31 *μm*, J_R=3.01 and r_{ext}=0.9.

In the following, in relation to the discussion provided in section II, we will explore the impact on optical pulse properties of variations in the external cavity length, the bias current and optical feedback strength. Firstly, we investigate the influence of L_{ext} on the characteristics of the ultrashort pulses. The range of L_{ext} we choose is the same as the one in inset (II) of Fig. 1 where ultrashort pulses are generated. Figure 3 shows the characteristics of the ultrashort pulses as a function of L_{ext} when J_R=3.01 and r_{ext}=0.9. In Fig. 3, the pulse width and repetition frequency both decrease with increase of L_{ext} (Fig. 3(a)), whereas the pulse peak increases with increase of L_{ext} (Fig. 3(b)).

Secondly, we investigate the influence of J_R where figure 4 shows the characteristics of the ultrashort pulses as a function of J_R with L_{ext}=100.26 *μm* and r_{ext}=0.9. As shown in Fig. 4(a), the pulse width decreases with increase of J_R, whereas the repetition frequency almost linearly increases with increase of J_R. In Fig. 4(b), the pulse peak increases with increase of the injection current.

Finally, the influence of r_{ext} on the characteristics of the ultrashort pulses is presented in Fig. 5. In Fig. 5(a), both the pulse width and repetition frequency decrease with increase of r_{ext}. In Fig. 5(b), when r_{ext} increases, the pulse peak increases.

From Figs. 3-5, we can see that simulation results are in accordance with the relevant discussion in Section II. Furthermore, increase of injection current can further decrease the pulse width and increase the repetition frequency of the ultrashort pulses after the choices of L_{ext} and r_{ext} are made.

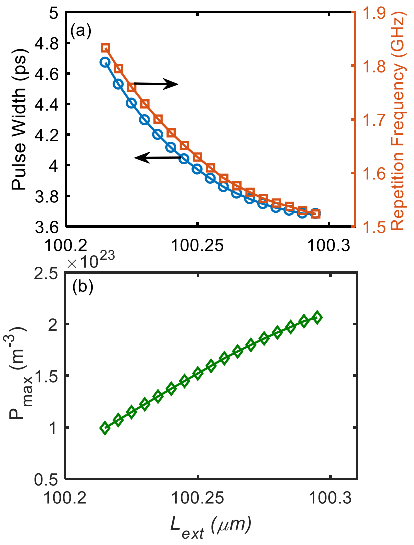

Fig. 3. *Influence of L_{ext} on the characteristics of the ultrashort pulses when J_R=3.01 and r_{ext}=0.90. (a) Influence of L_{ext} on the pulse width and repetition frequency, (b) Influence of L_{ext} on the pulse peak.*

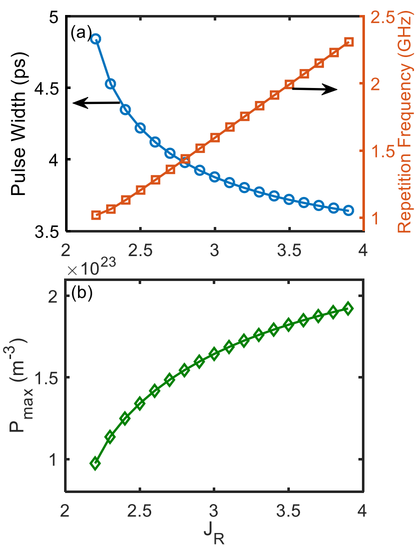

Fig. 4. *Influence of J_R on the characteristics of the ultrashort pulses when L_{ext}=100.26 μm and r_{ext}=0.90. (a) Influence of J_R on the pulse width and repetition frequency, (b) Influence of J_R on the pulse peak.*

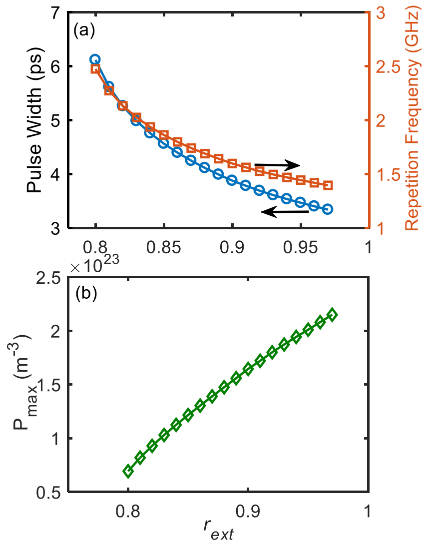

Fig. 5. *Influence of r_{ext} on the characteristics of the ultrashort pulses where L_{ext}=100.26 μm and J_R=3.01. (a) Influence of r_{ext} on the pulse width and repetition frequency, (b) Influence of r_{ext} on the pulse peak.*

4. Conclusion

In this paper, it is predicted, for the first time as far as we are aware, that ultrashort pulses can be generated using a semiconductor laser subject to strong optical feedback from short external cavities. Numerical results show that ultrashort pulses are generated periodically with respect to the external cavity length (L_{ext}) and the period is $\lambda_0/2$. Within this period, the range of L_{ext} for the generation of the ultrashort pulses is $\lambda_0/15$ for which the pulse width decreases respectively with increase of L_{ext}, the injection current (J) and the feedback coupling factor (κ). The repetition frequency of the pulses linearly increases with increase of J but decreases with either increase of L_{ext} or κ. Increase of L_{ext}, J or κ all cause increase of the pulse peak.

The applicability of the proposed scheme is envisaged primarily in the context of photonic integrated circuits. Thus one may consider that both the laser and external cavity, as short as 100 *μm* (corresponding to $f_{RO}\approx 0.01 f_{ext}$), can be monolithically integrated into one single device [20]. Also, tuning of the external cavity length within a small range of $\lambda_0/2$ is feasible by tuning the operating temperature of the laser or integrating a phase section in the external cavity [33]. There are also various means to achieve strong feedback such as integrating a semiconductor optical amplifier (SOA) in the external cavity [21, 34] and applying high reflectivity coating on the reflector [22]. We believe that this work provides the basis for designing ultrashort pulse generators for incorporation in future photonic integrated optical circuits.

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