Class A mode-locked semiconductor ring laser

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We experimentally demonstrate low-repetition-rate mode-locked operation of a macroscopic semiconductor ring laser. Since antiphase periodic pulses are observed only when the two directions of operation are constrained to spatially overlap in the semiconductor medium, we interpret this regime as a result of coupling and competition between clockwise and counterclockwise emission directions. Because of its time constants and the possibility of unidirectional operation, the device could be highly suitable for the generation of temporal cavity solitons. © 2012 Optical Society of America

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Semiconductor lasers are used in many experiments for the generation of transverse cavity solitons in injected microcavities [1,2] or bistable lasing schemes [3-5]. One of the most fascinating theoretical predictions in this domain is the existence of cavity light bullets [6] or three-dimensional cavity solitons. In spite of promising observations in frequency-selective feedback experiments [7] or during transients in coupled semiconductor microcavities [8], three-dimensional cavity light bullets have not been proved to be stable yet. Among the mechanisms leading to their destabilization, theoretical studies have indicated the relative time scales of material and optical variables to be of crucial importance. Indeed, most numerical studies about cavity light bullets have been performed in the limit of an instantaneous medium [6,9], which of course eliminates this question. When material time scales have been taken into account, the slow carriers have been shown to lead to merging of light bullets [10]. Another source of instability for cavity light bullets is the interaction between forward and backward propagating pulses, as underlined in recent reports about temporal cavity solitons in a fiber ring cavity [11] and pulsed solutions in semiconductor microring lasers [12].

In view of these observations, it is clear that a strongly multimode Class A semiconductor ring laser (carriers relax much faster than the electric field [12]) able to operate unidirectionally would be an excellent candidate for the generation of cavity light bullets. In this Letter, we present an implementation of such a system. We show that when spatial segregation of clockwise (CW) and counterclockwise (CCW) emission is prevented, competition between both directions leads to bistability and mode-locked operation, showing the potential of the system for light localization along the direction of propagation.

The experimental setup is illustrated in Fig. 1. The active medium is a GaAs broad-stripe amplifier (4 mm long and 200 μm wide) designed to operate around 980 nm [14]. The specified reflectivity of the front and rear facet is of the order of 3 × 10^-4, and stand-alone lasing has not been observed even when driving the diode up to 4 A.

All the optics used are coated for near IR. In both emission directions, the fast axis of the diode is nearly collimated using two equal high-NA spherical lenses (C1, C2).

Because of strong astigmatism resulting from the stripe geometry of the active medium, two additional identical cylindrical lenses (L1, L2) are required inside the cavity to compensate the effect of diffraction along the largest dimension of the stripe. They are set such that the center of the cavity is an image plane, where the spot size below threshold is about 2 mm. An iris (I, minimal aperture 1 mm) is placed in this position, which allows for limiting of the spatial degrees of freedom of the system [15]. The four mirrors used for the ring cavity are dielectric high-reflectivity mirrors (more than 99%).

The ring has been implemented with different cavity lengths from 62 cm [free spectral range (FSR) about 487 MHz] to 88 cm (FSR about 340 MHz).

A beam sampler (BSa) couples out CW and CCW beams in two opposite directions where all the instruments for detection are located. The beam sampler couples out 1% of the internal ring cavity power. The output of the cavity is studied in the temporal domain using a fiber-coupled fast photodetector (FPD) with 8 GHz bandwidth. One of the detectors is connected to a radio frequency spectrum analyzer (RF). The time-averaged power is monitored with a power meter (PM). The optical spectrum is also monitored by a commercial fiber-coupled optical spectrum analyzer (Agilent 86140) with a nominal resolution of 0.07 nm. Both directions of the emission have the same spontaneous and emission lasing spectra.

Figure 2 shows the time-averaged LI curve taken for the CW (blue curve) and CCW (red curve) direction. Figure 2(a) shows a continuous onset of lasing emission. Typically, the lasing mode power outside the ring is around 0–22 mW. Both directions of emission have the...
same threshold current, around $I_{th} = 1.5 \, \text{A}$, though a different slope—one (CW) is predominant compared to the other (CCW), depending on alignment. No bistability between CW and CCW is observed.

Figure 2(b) has been obtained by mechanically closing the diaphragm (I) inside the cavity. Its effect is to confine the dynamics in a reduced region of space, thereby reducing the transverse degrees of freedom of the system [15] and avoiding complex transverse effects expected to take place in broad area semiconductor lasers [16], especially in ring geometries [17]. The laser threshold is not altered, but a large hysteresis loop between CW and CCW is now observed around 2.1 A when ramping up and down the pumping current. This hysteresis loop indicates directional bistability, the time-averaged laser intensity being mostly CW or CCW depending on previous history.

For current values above the bistability region, the power in the CW and CCW directions increases linearly but with different efficiency, as shown in Fig. 2(b). Although the details of the curve depend on specific realizations of the experiment (precise lens and mirror alignments), the generic behavior corresponds to the one described here.

Bistability has long been observed in micrometer-sized semiconductor ring lasers, and the absence of bistability at the lasing threshold has been attributed to linear coupling between the two directions of emission [18]. Even if this linear coupling also clearly exists in the present device, the fact that bistability disappears when the iris is opened and is restored when the iris is closed indicates that in the present case, competition between the CW and CCW directions takes place only when they are constrained to share the same active medium. In the following, the iris is kept closed so as to maximize competition between the two directions.

Figure 3 shows the power spectrum as a function of current. Near the laser threshold, only two peaks are observed (others exist at higher frequencies), corresponding to longitudinal mode beatings. Upon increasing the current, many other peaks appear, indicating low-frequency instability and its harmonics around each longitudinal mode that we associate to linear coupling between the two emission directions [18,19], leading to multimode alternate oscillations. One striking feature is the total absence of relaxation oscillations, which would be evident as a broad peak whose frequency scales with the square root of the distance from threshold, as in any semiconductor laser. Thus, we can conclude that (as can be expected from the physical parameters of the cavity), this semiconductor laser is Class A in the classification of [15].

Although in general the many frequencies present in the spectra lead to disordered antiphase dynamics, in very sensitive alignment conditions a perfectly periodic regime involving many cavity modes can be observed as shown in Fig. 4, which shows the signal recorded with the fast photodetector for the CW (red) and CCW (blue) directions of emission. Figure 4(a) is slightly above the laser threshold, $I = 1.6 \, \text{A}$. Figure 4(b), obtained at $I = 1.7 \, \text{A}$, shows a perfectly periodic regime. Figure 4(c) is a magnification of Fig. 4(b) showing the upward pulses (in CCW) equally spaced among them and the corresponding drops in the CW direction. The apparent lag between the upward and downward pulses results from the output coupler not being in the center of the cavity, but a pulse in CCW and a drop in CW actually coincide in the active medium. The observed pulse duration is 300 ps (limited by the 1 GHz oscilloscope bandwidth) at 487 MHz repetition rate. These pulses (whose modulation depth is close to 100%) correspond to strongly multimode emission with a fixed phase difference between all the modes in the absence of any external forcing or phase reference, and we therefore interpret this regime as a passively mode-locked situation. Corresponding power spectra are shown in Fig. 5. Since this situation was not observed without constraining the two waves to overlap in space and shows antiphase dynamics, we propose that it is due to the competition between the CW and CCW emission directions. By further increasing the pumping current the fixed phase relation between the laser modes breaks, resulting in a complex situation,

![Fig. 2. (Color online) (a) Time-averaged LI curve with open diaphragm (b) Time-averaged LI curve with closed diaphragm.](image1)

![Fig. 3. (Color online) Power spectrum in the bidirectional case, showing beat notes between modes (340 and 680 MHz) at threshold followed by multimode alternate oscillations and their (sub)harmonics. On the right, power spectra at 1.55 A (bottom), 1.57 A (middle), and 1.64 A (top).](image2)

![Fig. 4. (Color online) Experimental time traces of the intensities for different current level for the CW (blue curve) and CCW directions (red curve) at (a) $I = 1.6 \, \text{A}$, (b) $I = 1.9 \, \text{A}$, (c) magnification of (b), $I = 1.9 \, \text{A}$, (d) $I = 2.3 \, \text{A}$.](image3)
as shown in Fig. 4(d) and the inset of Fig. 5. We note that the mode-locked regime has not been observed with the diaphragm open, the ring cavity passing directly from Fig. 4(a) to 4(d).

Even if the realization of mode locking in a Class A ring laser is a good indication for the potential of the device for the generation of temporal cavity solitons, it is known that the stability of temporal cavity solitons depends on pure unidirectional emission [11]. This can be achieved in this semiconductor ring laser by inserting two 30 dB optical isolators in the cavity (resulting in a total length of 110 cm, FSR = 272 MHz). When this is done, CCW direction is suppressed below the PM resolution (≤ 1 μW) and purely unidirectional emission takes place. In this case, neither low-frequency instability nor periodic pulses or drops have been observed, reinforcing the interpretation of the latter as due to linear coupling and competition between CW and CCW emission directions.

In conclusion, we have demonstrated that low-repetition-rate passive mode locking can be achieved in a Class A ring semiconductor laser provided the competition between CW and CCW emission directions is strong enough. Since the device can also be constrained to operate in a purely unidirectional way, the system could be very useful for the generation of temporal cavity solitons in an active configuration.

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