Effect of Optical Feedback on 60-GHz Colliding-Pulse Semiconductor Mode-Locked Lasers

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***Abstract*—We have experimentally investigated on the effects of optical feedback on the performance of monolithic colliding-pulse passively mode-locked semiconductor lasers operating at 60 GHz, designed to be efficient sources of millimeter-wave electrical signals. The characteristics of the optical-to-electrical converted signal are investigated for a long and a short external cavity by means of an external photodiode and by using the saturable absorber of the device as an intracavity photodetector. For a power feedback ratio larger than 10^{-3}, the linewidth of the millimeter-wave signal is severely broadened with respect to the value of 230 kHz measured in unperturbed conditions. We also report that optical feedback causes central frequency shift and instability, and a reduction of the useful colliding-pulse mode-locked operating region in the biasing parameters of the device.**

***Index Terms*—Millimeter-wave generation, mode-locking, optical feedback, optoelectronic integrated circuits, semiconductor laser.**

I. INTRODUCTION

MONOLITHIC semiconductor mode-locked lasers (MLLs) are compact and robust sources of short optical pulses at high repetition frequency [1]–[4]. They are generally fabricated using the split-contact technique, resulting in devices with two longitudinal sections: One is the gain section that is forward biased; the other section can be either reverse biased in dc, operating as a saturable absorber (SA) for passive mode-locking, or it can be used as a gain–loss modulator by applying a radio-frequency (RF) electrical drive signal to achieve active mode-locking.

Besides conventional passive MLLs, where the SA section is placed at the device end, colliding-pulse mode-locked (CPM) lasers have been also demonstrated, where the SA is precisely located in the middle of the cavity [1], [3], [4]. In CPM devices, two optical pulses counterpropagate in the cavity, saturating the SA at the same time. Hence, the repetition frequency of the optical pulse train is doubled with respect to a conventional MLL of the same length. For this reason, CPM lasers are ideal candidates for the generation of optical signals with very high repetition frequency, without the need for an unpractical shortening of the laser cavity length.

Recently, there has been growing interest for the generation of microwave and millimeter-wave electrical signals using a monolithic optoelectronic approach, by combining in a single optoelectronic integrated circuit (OEIC) an MLL and a fast photodetector [5]. In such practical situations, the MLL or CPM laser could experience optical feedback generated by discrete reflections, either caused by discontinuities of the optical waveguide in the monolithic chip (arising from integration with other devices such as semiconductor optical amplifier, modulator, photodetector), or occurring at the device package interfaces or from other optical devices placed along an optical fiber.

In this work, we report on experimental investigation about the effects of optical feedback on the performance of passive CPM lasers operating at 60 GHz. Results show that feedback levels of the order of 10^{-3} in power are detrimental for mode-locking operation, causing broadening of the RF electrical signal extracted from the pulse train, as well as narrowing of the useful ML region, thus making proper biasing of the device more critical in order to obtain mode-locking.

II. EXPERIMENT

Several CPM lasers were fabricated at Glasgow University in GaAs–AlGaAs double quantum-well material emitting at 870 nm [6]. The lasers consist of double section ridge waveguides of 1250-μm total cavity length, with an SA of 25- or 50-μm length placed in the middle of the cavity. The reversed biased SA can also be used as an intracavity photodiode to convert the optical CPM signal to the electrical domain. For this purpose, the SA was fabricated with a planar contact pad structure in the ground-signal-ground (GSG) configuration, allowing the use of a coplanar microwave probe to monitor the device operation. Fig. 1 reports two scanning electron micrographs (SEMs) illustrating details of the fabrication of a 25-μm SA with GSG pad, that was obtained by etching two lateral regions down to the bottom n-layer before contact deposition.

The devices were characterized in the presence of optical feedback using the setup shown in Fig. 2, for the two cases of a long and a short external cavity. For the long external cavity ($L_{\text{ext}} = 0.2$ m), the optical output was collimated onto a mirror using an antireflection coated (ARC) lens and a variable optical

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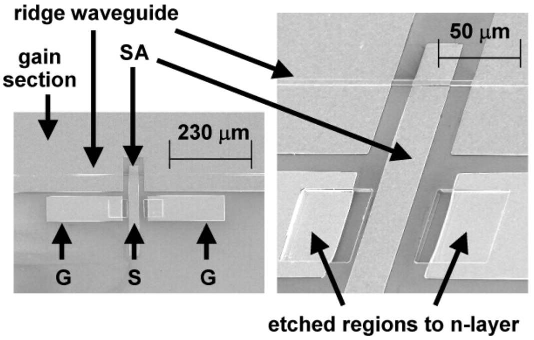


Fig. 1. SEM micrographs of the fabricated CPM devices, showing details of the ridge waveguide and the in-line SA section with the coplanar GSG pads to be contacted by an RF probe.

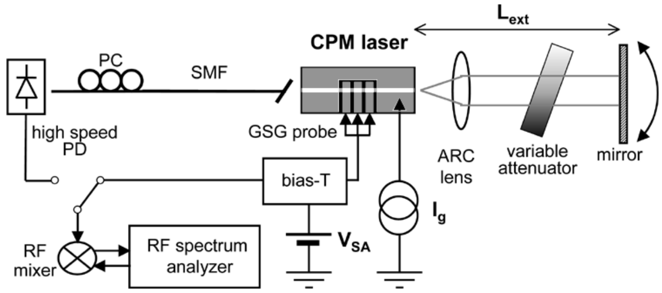
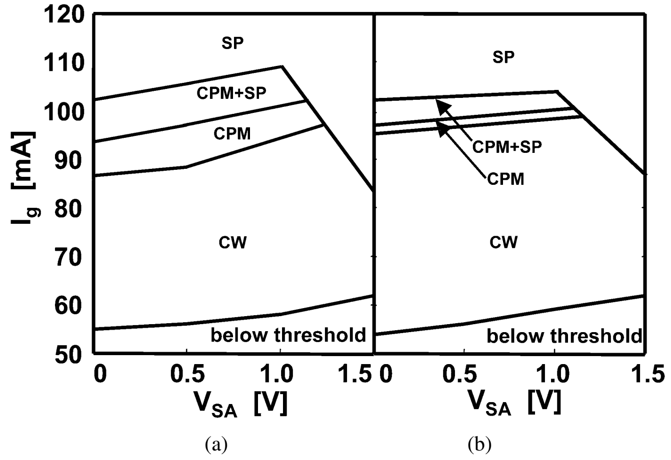


Fig. 2. Scheme of the experimental setup used to test the CPM lasers in presence of optical feedback. The SA is contacted by an RF coplanar probe. SMF: Single-mode fiber with tilted tip. PC: Polarization controller.

attenuator. To simulate as closely as possible the effects of reflections generated from within an OEIC, a short external cavity ($L_{\text{ext}} = 7$ mm) was also arranged by placing the mirror directly in front of the laser facet. In this case, the optical feedback was adjusted by tilting the mirror, and its strength was calculated by propagating the emitted Gaussian beam to the mirror and back to the laser facet. For both configurations, the optical feedback strength is given by the factor $F \equiv P_{\text{feedback}}/P_{\text{out}}$, i.e., the ratio of the power reflected onto the laser facet to the emitted power.

The characteristics of the RF electrical signal obtained from the CPM lasers were analyzed using an RF spectrum analyzer in connection with an harmonic mixer. The electrical signal was extracted either using the SA, or via a fiber-coupled fast photodiode (New Focus 1004). Care was taken to reduce unwanted optical feedback from the monitor path, by using a single-mode fiber with a 15° tilted tip on the butt-coupling side, and by inserting a polarization controller so that the light back-reflected from the external photodiode was cross-polarized with respect to the laser mode.

Typical laser threshold current values were around 55 mA at 25 °C, and the CPM regime was observed around 90 mA, where an output average optical power of 10 mW was measured. A typical regimes' map in the plane V_{SA}-I_g (where V_{SA} is the dc reverse voltage applied to the SA, and I_g the forward gain section current) are shown in Fig. 3(a). Besides the continuous wave (CW) and 57-GHz CPM regimes, a self-pulsation regime was also reported (either alone, or superposed to CPM), with large regular pulses at 1-GHz frequency. The full-width at half-maximum linewidth of the millimeter-wave electrical signal in CPM regime was 230 kHz.



(a) (b)

Fig. 3. Maps of the different operating regimes obtained by varying the forward current applied to the gain section (I_g) and the reverse voltage applied to the SA (V_{SA}). SP: Self-pulsation. (a) Unperturbed operation, without optical feedback. (b) Optical feedback strength $F = 2.5 \cdot 10^{-2}$. The presence of feedback narrows the region of useful CPM regime.

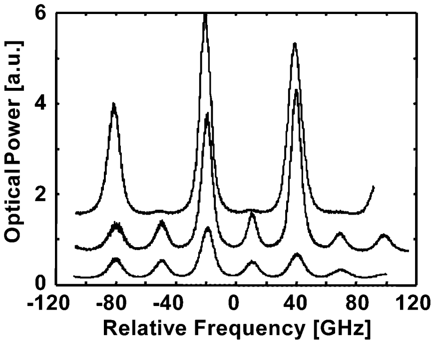


Fig. 4. Optical spectra of the CPM laser for different forward current values I_g applied to the gain section, with $V_{\text{SA}} = 0.5$ V. Traces are vertically offset for clarity. From bottom to top: $I_g = 63$ mA (threshold); $I_g = 82$ mA (CW); $I_g = 94$ mA (CPM, showing suppression of odd modes).

Fig. 4 reports optical spectra of the device recorded for increasing forward current. The top trace reveals that only evenly spaced modes are active, while odd-numbered modes are suppressed by 17 dB. This is a sign of well-developed CPM operation, as reported in [3].

As the devices were designed to be monolithic optoelectronic sources of millimeter-wave signals, a thorough characterization of optical pulse properties (pulsewidth, chirp, etc.) was not carried out, because the optical output was not intended to be propagated along an optical fiber or in other way used.

Several different devices were tested in the presence of optical feedback obtaining repeatable results, irrespective of the SA length of the specific laser. As a basic result, it was observed that optical feedback was detrimental for the operation in the CPM regime, as it can be seen by Fig. 3(b) that reports the regimes' map for a feedback factor $F = 2.5 \cdot 10^{-2}$. The range of the useful CPM region was reduced by a factor of five along the gain current coordinate. More severe effects were observed in the form of an enhancement of the RF signal linewidth at 57 GHz, reported in Fig. 5. At a feedback level $F = 10^{-3}$, the linewidth starts to broaden, and a linewidth increase by one order of magnitude was observed for a feedback level $F = 10^{-2}$

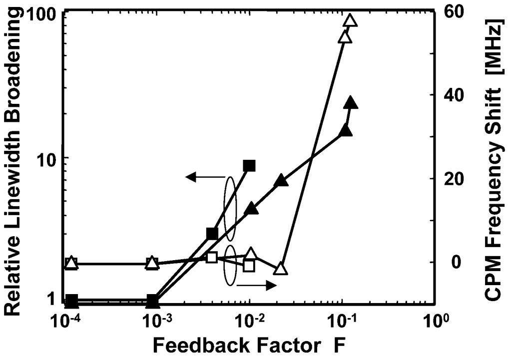


Fig. 5. Effects of optical feedback on the characteristics of the RF signal extracted from the SA in CPM regime. The graph reports the relative linewidth broadening of the RF signal (full symbols), and the CPM frequency shift (open symbols), for both the short external cavity (squares) and the long external cavity (triangles).

and $F = 5 \cdot 10^{-2}$ for the short and long external cavity, respectively. For the case of long external cavity, a positive detuning of the CPM oscillation frequency was also reported. Besides the instantaneous linewidth, also the long-term stability of the CPM frequency was degraded by optical feedback. As an example, the typical CPM frequency drift was around 4 MHz in 10 s for the unperturbed lasers, and this figure doubled when an optical feedback of $F = 5 \cdot 10^{-2}$ was applied. The optical spectrum of the laser was not affected by optical feedback, as long as the device was operated in the CPM regime.

In our investigations, no effect was observed when the phase of the optical feedback was varied, for both the short and long external cavity. In fact, for a given feedback strength, the RF signal linewidth and frequency did not change significantly when the distance of the external mirror was finely varied through a complete free spectral range of the RF signal (i.e., the mirror position was scanned over more than 3 mm for the case of the long cavity).

III. DISCUSSION

It is interesting to check in which feedback regime the CPM devices were operated throughout the present work, with reference to the classification introduced by Tkach and Chraplyvy for single-mode CW lasers [7]. The feedback level at which the RF linewidth starts to broaden $(F = 10^{-3})$ lies in Zone IV, the so-called coherence-collapse regime. Coherence-collapse is likely to affect negatively the phase-locking relation between the longitudinal modes of an MLL.

It is worthwhile to make a comparison with the results reported by Solgaard and Lau in [8], which is the only published work to date reporting on optical feedback applied to monolithic passive MLLs. Solgaard and Lau observed effects that are dissimilar from those reported here: namely, they reported beneficial effects of optical feedback on the RF linewidth (which could be narrowed up to a factor 100) and observed feedback-phase effects. Differences between the present work and [8] can be explained by the fact that the devices under test were very different in their solitary behavior without feedback. In fact, the unperturbed RF linewidth of the devices of [8] was 20 to 50 times larger than those of our devices. For a large linewidth MLL, a beneficial effect from optical feedback can be expected, similar to the classical case of a CW laser, as reported by Schunk and Petermann [9]. When optical feedback is essential in reducing the linewidth of an oscillator, this effect generally depends on the phase of the feedback.

Conversely, in our case, regular mode-locking oscillation is disturbed (and not favored) by optical feedback, which is strong enough to bring the laser close to coherence collapse. In analogy, a CW laser operating in this regime loses coherence, and feedback phase has no effect on the linewidth [9], similar to our observations.

IV. CONCLUSION

We have experimentally investigated the effects of optical feedback on CPM lasers operating at 60 GHz. Results showed that for a power feedback ratio larger than 10^{-3}, the characteristics of the millimeter-wave signal are negatively affected, leading to linewidth broadening, central frequency shift and instability, and to a severe reduction of the useful CPM operating region.

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