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Abstract: In this paper, we present the first tunable extended cavity integrated passively mode-locked laser realized in an anticolliding design. The laser is realized as an InP-based photonic integrated circuit. A detailed study of the laser performance under various operating conditions is presented. The evolution of the radio-frequency (RF) spectrum and optical spectrum with the injection current to the optical amplifier is investigated. Tuning over 9 nm is achieved by injecting current in a distributed Bragg reflector section. We demonstrate that tuning of the optical spectrum toward shorter wavelengths, which increases absorption in the saturable absorber section, leads to an improvement of the mode-locked laser performance in terms of reduction of fundamental RF linewidth and reduction of the pulsewidths.

Index Terms: Mode-locked lasers, semiconductor lasers, tunable lasers.

1. Introduction
Passively mode-locked lasers are of great interest for developments in areas requiring broad coherent optical frequency combs and short pulses in such fields as telecommunication [1], generation of microwave signals, sensing [2], and optical clock recovery [3]. In order to achieve passive mode-locking, a semiconductor optical amplifier (SOA) is commonly combined with saturable absorber (SA) in the cavity. Saturation processes in these two elements lead to modulation of the light in the cavity at the cavity mode-spacing frequency and generation of short optical pulses [4]. Due to the relatively simple topology these lasers can be realized in the form of an integrated circuit on a single monolithic chip. The monolithic semiconductor lasers are a subject of particular interest in applications due to their compactness, robustness, simple integration with other optical components, power consumption and possible costs-saving that can be achieved by their application.

However, monolithic passively mode-locked lasers (PMLs) still cannot beat lasers realized as bulk optical systems in terms of stability, output power, pulse quality, and wavelength tunability. A large number of various monolithic semiconductor laser architectures were investigated in
order to overcome these issues. One of them is the so-called colliding pulse scheme. In this technique the intensity of the field inside the SA can be increased by colliding the pulse with itself [5] or with a counter-propagating pulse inside the SA [6]. In a linear cavity this method can be realized by placing the SA either in the middle of the cavity, where two counter-propagating pulses can interact, or by placing the SA next to one of the facets that act as a cavity end mirror. The latter geometry is the so-called self-colliding pulse configuration [7]–[9]. In this configuration, the pulse interacts with the SA together with its own reflection. It is considered to be more robust because it is less sensitive to the position of the SA. Recently in [10] it was shown theoretically that the best performance of self-colliding PML can be achieved when the SA is placed next to the low reflection facet, the output coupler. This geometry is called the anti-colliding configuration. The authors of [11] proved the superiority of such design over the PML where both facets have the same reflectivity. In our previous works [12], [13] we showed experimentally that placing of the SA next to the low reflectance mirror leads to an enlargement of the stable-mode-locking regime region and an increase of the optical power and stability in comparison to lasers with the configuration where the SA is placed next to the high reflectance mirror.

Another important characteristic of mode-locked lasers is pulse duration. One of the key issues for pulse shortening is to obtain optimal spectral detuning between the SA and SOA absorption and gain characteristics. This detuning can be achieved simply by applying a different bias on the SOA and SA [14], using a different layer stack composition for the gain and absorber sections [15] and tuning of the PML using intra-cavity filters such as distributed Bragg reflectors (DBR) [8]. The use of a DBR grating is a reliable way to achieve a controlled tuning of the ratio between the amount of gain and absorption in the gain and SA sections and to optimize the pulse characteristics. Moreover, a DBR based PML can be considered as a promising source for telecom applications, e.g., for WDM systems, where it is of importance to meet the requirements of the precise wavelengths of the laser modes.

In this work, we combine the anti-colliding design and the use of a DBR grating as a low reflectance mirror. The extended cavity design of the PML includes a 50% reflectivity DBR grating as output coupler. The design presented here, which will be described in detail in the next section, uses a very similar lay-out and has similar dimensions as the one presented in [13] where a broad-band 50% multimode interference reflector (MIR) was used as an output coupler. The cavity contains a passive waveguide section to allow for a shorter SOA section which reduces self-phase modulation effects compared to those in a conventional two-section FP laser. In addition the use of active-passive integration allows to adjust the length of the cavity by changing the length of the passive sections in order to meet specification of PML repetition rate for a particular application. Moreover, higher repetition rate can be reached by placing additional absorber in the middle of the cavity or at the distance from the reflector equal to the 1/n of the cavity length. The high reflectance mirror is based on a 100% reflecting MIR. The use of an on-chip mirror enables one to achieve a higher accuracy of the cavity length since there is no need for cleaved facets. For the same reason the device can be located freely on the chip, which allows one to proceed with further integration of PMLs with other optical components without restrictions concerned with location with respect to an edge of the chip [16]. In this paper, we will discuss the main consequences of using a DBR grating as an output coupler in the anti-colliding pulse mode-locking scheme, and demonstrate the improvement of the performance in terms of radio-frequency (RF) linewidth and pulse duration when the PML is being tuned towards shorter wavelength.

2. DBR Mode-Locked Laser Geometry and Material Characterization

The laser is designed as an InP photonic integrated circuit in the foundry technology of Oclaro Technology UK. The PML includes three active sections (100 μm long SA1 and SA2, 2 mm long SOA), a passive waveguide section, the DBR, and the multimode interference reflector (MIR). A schematic sketch is shown in Fig. 1(a). Such a design allows for switching the location
of the SA from the output coupler (OC) side to the end mirror (EM) side, simply by switching bias conditions on SA1 and SA2. SA1 and the SOA are electrically isolated by a 10 μm long isolation section. When a reverse bias is applied on SA1 and current of the same density is injected in SOA and SA2, the SA is located near the OC and an anti-colliding configuration is realized. In order to locate the SA at the other side, SA2 must be reverse biased, and other two active sections need to be forward biased using the same current density. All the active sections were based on an InGaAsP multi-quantum well waveguide core. The PML cavity has a length of 5.5 mm, where 3 mm is formed by a passive waveguide. The DBR grating was designed to have a 50% reflectivity in a spectral band of 4 nm width and centered at 1550 nm. However limitations in accuracy of the fabrication means there can be variations of 3 nm to the central wavelength. To minimize possible back reflections from the edges of the chip the output waveguides were angled with respect to the cleaved and AR-coated facets. At a first stage the SOA, SA and DBR grating were characterized separately using dedicated test structures. The chip with test structures was mounted on a temperature-controlled copper chuck at 18 °C. The output light was collected using lensed fibers with an antireflection coating. In Fig. 1(c) the net gain spectra (red curves) measured for current densities from 1000 to 2250 A/cm² are presented. The gain spectra were measured using a multi-sectional method [17]. The black curves in Fig. 1(c) represent net absorption spectra obtained at applied voltages from −0.1 V to −2.9 V. The arrow points direction of voltage increase. For these measurements a different multi-sectional active structure was used. This test structure consists of four sections, where the first and third sections are 50 μm long and the second and fourth are 1 mm long [see Fig. 1(b)]. The method is based on measurement of the transmission through the first reversely biased short section (absorber) of the ASE that is generated by the second and third sections that are forward biased with the same current densities. The first section was chosen to be short in order to provide a relatively low absorption so it does not fully deplete the ASE power from the SOA. The fourth section was always reversely biased to prevent optical feedback. The ASE signal which goes into the absorber can be measured by the forward biasing the first short section and second section.
and reverse biasing the third and fourth section. The total small signal absorption spectra of the SA as a function of reverse bias voltage and the total small signal gain spectra of the SOA as a function of injection current are presented in Fig. 1(c). The Fig. 1(c) shows significant red shift of the SA absorption spectrum with increasing voltage which is associated with quantum confined Stark effect.

The spectral shape of the reflection of the DBR was obtained by measuring the power of an external CW tunable laser signal reflected from the DBR while the active sections of the PML were reversely biased. The CW laser was tuned over 20 nm around the DBR reflectance band. Fig. 1(d) shows the reflected power as a function of the CW signal wavelength in a linear relative scale. The maximum of the reflected CW power spectrum was scaled to 0.5 since the DBR was designed to provide 50% reflection. An independent confirmation of this peak value is however not available. The DBR section was not contacted during this measurement. Even though the facet of the chip was AR coated, the raw experimental data had ripples with the period associated with the distance between the DBR and the facet at the end of the output waveguide. Fig. 1(d) shows the signal with these ripples filtered out. The reflection band has a width of 4 nm and it is centered at 1551 nm. This center wavelength is shifted towards a longer wavelength by 1 nm from the design value which is within the foundry specification.

2.1. Characterization of PML at $I_{DBR} = 0$

In this section we present a characterization of the PML when the DBR section was not contacted. The PML was characterized under the wide range of operating conditions in order to find optimal conditions to study an effect of the DBR tuning on the laser performance. The chip with the PML was mounted on a temperature stabilized copper chuck at 18 °C. The output light was collected using a lensed fiber with AR coating and sent to the other instruments through an optical isolator. The coupling loss from the chip to the fiber is estimated to be between 4 and 5 dB.

First, the performance of the PML in the self-colliding and anti-colliding configuration was evaluated. The Fig. 2 shows LI curves of self- and anti-colliding configurations under $-1.0$ V applied voltage on the SA. As predicted in [10], the output power in the case of anti-colliding design significantly exceeds the one in the self-colliding configuration. The threshold current was found to be 48 mA for the anti-colliding configuration and 41 mA for the self-colliding configuration. When operating the laser in the self-colliding configuration, it was operating in a CW regime over the whole range of applied operating conditions. For this reason we will not discuss operating of the PML in self-colliding configuration any further. The device in anti-colliding configuration operates in a mode-locked state for a wide range of operating conditions. A typical optical spectrum
measured at $I_{\text{SOA}} = 90 \text{ mA}$ and $U_{\text{SA}} = -1.3 \text{ V}$ is shown in Fig. 3(a). The optical spectrum was measured using a 20 MHz resolution optical spectrum analyzer. The spectrum shows a frequency comb centered at 1554 nm with a mode separation of 7.4 GHz. It must be noted that the optical spectrum is asymmetrically shaped and its central wavelength is shifted from the top of the DBR reflection band [see Fig. 1(d)] towards longer wavelengths by 2.5 nm. A red shift of the DBR reflection might be attributed to the thermal change of the refractive index. However, this effect would result in relatively small wavelength shift and in order to achieve 2.5 nm the DBR temperature should increase by more than 20 degrees. In mode-locked lasers the optical spectrum is influenced not only by the feedback spectrum but also by the gain of the SOA and the SA absorption profile [18]. The light propagating through the SOA at current $I_{\text{SOA}} = 90 \text{ mA}$ experiences a small-signal net gain that was measured at the current density $2250 \text{ A/cm}^2$. This gain spectrum is shown in Fig. 1(c) (the uppermost curve). At these operating conditions the small signal gain has a steeper change with the wavelength than the small signal absorption per round trip and its maximum is centered on 1542 nm. However, when the laser is above threshold and particularly in mode-locked operation, the light in the cavity can no longer be considered to be a small signal. Both gain and absorption are saturated. In this case, the carrier concentration and the gain value are reduced and the gain maximum is shifted towards longer wavelengths (as can be seen in Fig. 1(c) for the lower injection current densities). When the absorber is saturated the absorption per round trip is reduced but the direction of the slope stays the same, where light at the longer wavelengths experiences less loss. As it was mentioned before the DBR grating was designed to provide 50% reflection. This value is in the order of magnitude of the spectral variations of the gain and absorption. From this we can conclude that these gain and absorption dependencies can push the laser to operate at the red-shifted wavelength away from the DBR reflection peak. In the PML presented in [13], which was realized on the same chip, a few millimeters away from the devices presented here, the position of the optical output spectrum was centered at 1558 nm. The output spectrum of this laser which did not contain a DBR mirror was determined only by the gain and absorption profiles. Variation of the voltage in the SA leads to a change in the SA recovery time and it effects the detuning between the gain and absorption profile as well [18]. The measurements of the absorption show that indeed the absorption spectrum exhibits a red-shift with an increase of the applied voltage. Fig. 3(b) shows the dependency of the central wavelength of the PML on the voltage applied on the SA for $I_{\text{SOA}} = 100 \text{ mA}, 120 \text{ mA},$ and $140 \text{ mA}$. For all three injected currents the optical spectrum is being detuned over around 1.5 nm with the applied voltage towards longer wavelength. A similar shift of the central wavelength of around 2 nm with the applied voltage was observed in the case of the MIR based PML presented in [13]. An increase of the current in the SOA leads to a shift of the small signal gain spectrum towards shorter wavelength. However a red shift of the laser output of 1 nm was observed in the cases of both lasers (with MIR and with DBR) when the
SOA current was changed from 60 to 140 mA. This red shift is caused by the increase of the intra-cavity optical power and therefore increase of self-phase modulation effects in the SOA [19] or variation of the SA temperature due to the photocurrent generation [14].

For further characterization of the mode-locked laser RF spectra and autocorrelation (AC) traces were measured as a function of injected current and bias voltage. The RF beat tones were generated in a 50 GHz photodiode and measured using a 50 GHz spectrum analyzer. To obtain the AC traces the second harmonic autocorrelation intensity profiles were measured using an autocorrelator in a background free configuration. Since the laser output power was low, the signal was first amplified by a low noise erbium doped fiber amplifier (EDFA) and then sent through the polarization controller (PC) to the autocorrelator. The length of the erbium doped fiber was 42 m with a dispersion parameter of 10.8 ps/(nm km). More details of the influence of dispersion and non-uniform amplification caused by the EDFA on the AC trace can be found in [20]. The pulse formation was observed in the wide range of currents and voltages. The minimal observed AC width was 2.5 ps, which is more than two times less than the shortest one observed in the MIR based PML [13].

Fig. 4(a) shows the RF peak linewidth measured at −10 dB level as a function of $I_{\text{SOA}}$ and $U_{\text{SA}}$. At the low injected currents just above the threshold the laser exhibits CW operation with amplitude instabilities. In the rest of the range of applied bias conditions, a mode-locked state was maintained. However, depending on bias conditions the linewidth varies from 290 kHz to more than 40 MHz. Increasing the current to the SOA from 100–120 mA leads to a broadening of the RF linewidth till 40 MHz or more (dark red region in the middle) for the all applied voltages. When the $I_{\text{SOA}}$ was increased further a significant reduction of the RF linewidth was observed (dark blue region on the right). Fig. 4(b) shows an example of how the RF spectrum around the repetition rate changes with a scan of $I_{\text{SOA}}$ at $U_{\text{SA}} = −1.1 \text{ V}$. At the injected currents from 60 to 100 mA the RF spectrum represents a clear narrow line, whose central frequency is drifting towards lower frequencies with current. In [7] it was shown that such a significant change of repetition rate is caused by variation in saturation processes in the SOA and SA due to the change of optical power inside the cavity. Interestingly, in the case of the MIR based laser, severe tuning of the fundamental frequency was also observed, but the trend was opposite: as the current in SOA increases the RF peak shifts towards higher frequency. As it was shown in [7] the detuning of the fundamental tone can vary in opposite ways depending on the pulse energy. A further increase of $I_{\text{SOA}}$ leads first to a broadening of the RF peak and then a narrowing down. Measurements of the AC traces showed continuous broadening of the AC trace from 9 ps to 15 ps with increasing current.
2.2. Experimental Results of Tuning DBR

Tuning of the central wavelength of the optical comb is achieved by injecting current in the DBR grating section. Due to the plasma effect, the refractive index of DBR grating changes, which leads to a shift of the Bragg wavelength towards shorter wavelengths. However an increase of carrier density in the DBR section also leads to an increase of the absorption through the excitation of electrons to higher states in the conduction band. In addition to the DBR absorption, the SA absorption is wavelength dependent as shown in Fig. 1(c). When applying current on the DBR its reflection band is tuned towards shorter wavelength, which leads to an increase of the loss caused by the SA. Fig. 5 shows the measured dependency of the optical power on the current injected in the DBR section for three values of the current in the SOA, $I_{SOA} = 80, 107, \text{ and } 138 \text{ mA at } U_{SA} = -1.1 \text{ V.}$ The decrease of optical power with increasing $I_{DBR}$ was observed for all bias conditions presented. Fig. 5 shows that with increasing SOA current the reduction of output power becoming less pronounced. This can be explained by the intensity-dependent behavior of the SA, where light of higher intensity undergoes less absorption. However, the change of the energy in SA and SOA section, as well as spectral tuning, are causing significant changes in PML performance.

In order to investigate this aspect, the measurements of RF spectra, optical spectra and AC traces were performed for a range of $I_{DBR}$ values at several fixed operating conditions ($I_{SOA}$ and $U_{SA}$). For all of these conditions a tuning of the optical comb of more than 9 nm towards shorter wavelength was obtained. Fig. 6 shows an example of DBR tuning at $I_{SOA} = 80 \text{ mA at } U_{SA} = -1.1 \text{ V.}$ As it can be noticed from Fig. 4(a) the performance of the PML is not optimal at this operating point when $I_{DBR} = 0$. The RF linewidth at 10 dB level is 10 MHz, which is wider than those measured at the currents above 120 mA (the darkest region). However, the tuning of DBR leads to the increase of the losses in the cavity and the PML regime is being pushed towards threshold. Therefore tuning of the DBR from the optimal operating point makes the PML enter the unstable region which is indicated as a bright yellow region (100–120 mA) in Fig. 4(a). For this reason we present the results of the tuning measured at the current below 100 mA. The $I_{DBR}$ was scanned from 0 to 20 mA with a step of 1 mA. The RF peak at the fundamental frequency was observed at every value of $I_{DBR}$. Fig. 6(a) shows that injecting current to the DBR section leads to a repetition rate variation of more than 100 MHz, which can be associated by the decrease of optical power in the cavity. It also leads to a narrowing of the RF peak. At $I_{SOA} = 80 \text{ mA and } U_{SA} = -1.1 \text{ V,}$ no low frequency noise was observed. Fig. 6(b) shows the evolution of the optical spectrum, presented on a linear scale. It shows the shift of the optical comb towards shorter wavelengths with increasing $I_{DBR}$. Fig. 6(c) and (d) show the dependency on the DBR current of the central wavelength and the 10 dB RF linewidth at the fundamental frequency. Notice that the RF linewidth is significantly
decreased when the DBR current is applied and the laser is tuned to shorter wavelengths. In order to confirm the presence of the mode-locking state we also investigated the AC trace as a function of DBR current. For the whole range of injected currents the AC trace exhibits a background ratio of more than 30. Moreover, narrowing of the AC traces was observed with increasing DBR current. Fig. 6(e) shows the dependency of the AC width, extracted from the fitting of AC width, on DBR current. The reduction of pulse widths can be explained by a decrease of the intracavity power and therefore pushing the laser to operate closer to the threshold conditions. However, as the DBR current increases, the AC width reaches 3.95 ps at $I_{DBR} = 19$ mA, which is more narrow than the one observed near the threshold current without biased DBR at $U_{SA} = -1.1$ V. The AC trace measured at $I_{DBR} = 19$ mA and fitted by the Gaussian function is shown in Fig. 6(f) as blue circles and a red line respectively. It means an optical output pulse with length of 2.55 ps and a time bandwidth product of 0.46 is achieved. In Fig. 6(g) the optical spectrum indeed shows a near symmetrical distribution of this near Fourier limited pulse. The tuning of the wavelength of the short optical pulses results not only in a change of the absorption magnitude but also in variation of the time response of SA. In [21] the time response of the saturable Bragg reflector with a QW was characterized at different wavelengths. It was shown that depending on the...
wavelength, a different ratio between a fast (in the order of the pulse duration or shorter) and slow contribution (longer than the pulse duration) in the absorption recovery can be achieved. When the incident wavelength was below the exciton peak wavelength the absorption recovery was mainly dominated by the slow component. At the wavelength around the exciton peak and above, the fast recovery process was more pronounced. As the wavelength of the incident light is increased the absorption reduces and the total impact of the absorption temporal response on the pulse shaping reduces. Thus, by tuning the DBR spectrum towards a shorter wavelength a faster and a stronger saturable absorption can be achieved in the SA. In addition the increase of absorption at shorter wavelength leads to the decrease of the duration of the temporal window in which a net positive gain remains. This also tends to reduce the noise after the pulse is gone. The data in Fig. 6(d) show that indeed the RF linewidth is decreased down to 200 KHz, which is less than minimum RF linewidth (290 kHz) obtained without tuning the DBR spectrum.

3. Conclusion
The first tunable integrated linear mode-locked laser with anti-colliding pulse design was presented. The laser with 7.35 GHz repetition rate was designed using standardized library components of a photonic integration technology platform. The PML showed relatively poor performance when no current was applied to the DBR section. Even though the laser layout repeats the one presented in [13] with the only difference of using a DBR mirror instead of a broad-band MIR as an OC, the DBR PML shows reduced stability over the all range of operating conditions. This may be attributed to the tuning of the DBR with respect to the SOA and SA gain and absorption spectra as well as the presence of feedback from the facet of the chip. Carrier injection into the DBR section is needed to get to a good performance of the laser. It leads to the total tuning range of 9 nm, which to our knowledge is the largest tuning range achieved by integrated DBR mode-locked laser. It was demonstrated that spectral tuning of the signal towards shorter wavelength leads to the significant improvement of the signal in terms of RF linewidth, pulse duration and optical bandwidth, caused by the sharpened temporal response of the SA. Observation of autocorrelation traces showed a reduction of AC width down to 3.95 ps. Near Fourier limited pulses were produced at the highest DBR current levels. The RF linewidth measured at −10 dB level below the peak was reduced from 10 MHz down to 215 kHz. These results can be used for future designs of DBR based PMLs. To continue the investigation of the influence of the position of the optical spectrum on the PML performance, the DBR reflection band can be designed to have an even shorter central wavelength than the one presented here. To increase the optical spectral bandwidth the DBR reflection band can be in principle be broadened by increasing the strength of the grating. Technologically this is very challenging, however but in principle it can allow for a reduction of the optical pulse duration. However, the influence of the dispersion in DBR grating is not yet investigated. In order to avoid using DBR gratings the tunable filtering can be achieved by combining series of Mach-Zehnder interferometer of different delay between arms similarly as it was shown in [22]. A 60 nm tuning range of the CW laser wavelength was achieved by varying the phase delay between the Mach-Zehnder interferometer arms. This concept can be also used for mode-locked lasers realized in linear and in ring configurations.

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