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On-Chip Colliding Pulse Mode-locked laser diode (OCCP-MLLD) using multimode interference reflectors

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Abstract: We report the achievement of colliding pulse mode-locked (CPM) regimes on a novel on-chip mode locked laser diode (OCCP-MLLD). The advantage of the resonator structure that we present is that the end-mirrors are defined through multimode interference reflectors (MIRs), which provide precise control of the cavity length avoiding the need for cleaved facets. This simplifies positioning the saturable absorber at the center of the resonator to achieve the colliding pulse mode-locked regime and double the repetition rate, reaching the millimeter wave frequency range. An additional advantage is that the pulsed output is delivered within the Photonic Integrated Circuit chip for further processing (i.e. modulation). We demonstrate a colliding pulse passive mode locked regime with pulse widths below a picosecond ($\Delta\tau = 0.64$ ps), timing jitter $\sigma_T = 75$ fs and amplitude noise $N_{AM} = 0.012$ dBc. The samples were fabricated in a generic InP foundry service through multi-project wafer (MPW) runs.

OCIS codes: (250.5300) Photonic integrated circuits; (140.4050) Mode-locked lasers; (130.3120) Integrated optics devices; (250.5960) Semiconductor lasers.

References and links

1. Introduction

Colliding pulse mode-locked (CPM) laser diodes are well known sources of ultrafast and ultrashort optical pulses [1]. Pulse durations between 0.52 to 1.28 ps have been generated, with pulse repetition rates in the range 40–500 GHz [2], with Fourier-transform-limited operation routinely achieved. In addition to excellent pulse characteristics, CPM laser diodes offer pulse shortening and increased repetition rates. These advantages derive from locating the saturable absorber at the center of the resonator. The saturation of the absorber is enhanced by the fact that the structure allows two counter-propagating pulses to coexist in the cavity which reach to it simultaneously. The generation of short optical pulses is essential for ultrafast data processing, high bit rate time-division multiplexed communication systems, and picosecond optoelectronic applications [3]. As these components have been shown capable of generating pulses at repetition rates in excess of 1.5 THz [4], a potential field of application is the generation of carrier wave frequencies in the millimeter-wave range for broadband wireless communications [5].
Moreover, the simplicity of their structure allows to be implemented in a photonic integrated circuit (PIC) [6], which would allow developing compact system around it adding functionalities [7]. Some previous examples where the benefits of on-chip integration bring to mode-locked laser diodes are the combination of different mode-locked sources for wavelength division multiplexing (WDM) [8], or an increase of the optical pulse average power including a tapered semiconductor optical amplifier at the output [9]. However, the common approach for mode locked laser diodes to define the resonator by cleaved facet mirrors is ruled out for PIC integration [3, 10].

Two main approaches have been proposed to integrate mode-locked laser diodes on-chip. The first one is using ring resonators, which offer lithographic control of the cavity length [11]. However, ring structures support two counter-propagating fields, requiring the inclusion of special structures within the ring such as asymmetries [12] or s-shape structures [13], in order to suppress one propagation direction. The second approach uses a cleaved facet on one end of the cavity, and a Distributed Bragg Reflector (DBR) on the other [14]. This technique has recently been improved, demonstrating mode-locking when a surface-etched grating is used [15], with simpler fabrication process than the fairly complicated DBR.

Recently, different types of broadband on-chip mirrors have been reported, which allow defining the cavity resonator within the chip. One approach is through Sagnac Loop Reflectors (SLRs), composed of an optical multimode interference (MMI) coupler in which two of its outputs are connected to each other with a loop waveguide [16]. These type of mirror structures have been used in linear arrayed waveguide grating multi-wavelength lasers [17]. An alternative approach employs multi-mode interference reflectors (MIRs), which are novel on-chip mirror compact structures that require only the use of a deep etch fabrication step [18]. Fabry–Perot laser structures have been recently demonstrated with resonator cavity lengths down to 415 µm [19]. Using this type of mirrors, we have recently observed passive mode locked regimes of operation, with repetition rates determined by the cavity length [20]. In this approach, we tried locating the SA at ¼ of the cavity length to achieve a 4 times increase of the repetition rate to reach millimeter-wave frequencies. However, the uncertainty on the MIR mirror length led to a failure in precisely locating the SA, and only fundamental mode locking was achieved.

In this work we report the observation of passive colliding pulse mode-locked regimes in an extended cavity laser structure using MIR reflectors to define the resonator on-chip. We have located the saturable absorber (SA) at the center of the cavity, defining the resonator symmetrically around it. Therefore, the precision with which the SA is positioned at the center only depends on the lithographic process tolerances, down to the nanometer range. As we have observed, this is a critical advantage, since CPM requires a precise location of the SA as the two counter-propagating pulses in the resonator have to enter simultaneously into the SA to doubly saturate it [1]. Our results show pulse widths down to \( \Delta \tau = 0.64 \) ps, phase noise \( \sigma_T = 75 \) fs, and amplitude noise \( N_{AM} = 0.012 \) dBc, close to the best values previously reported mode-locked structures [21–23]. The repetition rate that we selected lies within the E-band frequency range of the millimeter-wave spectrum (60 GHz - 90 GHz), aiming to wireless communication carrier wave generation.

### 2. Device Description

We present two extended cavity linear laser designs which include semiconductor optical amplifiers (SOA), a saturable absorber (SA) as well as passive waveguides (PW) and multimode interference reflectors (MIRs). The laser was designed as a Photonic Integrated Circuit, using a library of standardized building blocks (BBs) and fabricated within a commercial multi-project wafer (MPW) run available through SMART Photonics InP active-passive integration foundry service [24]. The structure of the OCCP-MLLD is shown Fig. 1(a). The saturable absorber (SA) is located at the center of the resonator cavity by defining the structure symmetrically from each side of the SA. The first element to be included is
optical gain through semiconductor optical amplifiers (SOAs). On each side of the SA, we locate an SOA with the same length. The SOAs is followed by an active-passive transition and a passive waveguide. This waveguide, which is necessary to connect the SOA to the Multimode interference reflectors (MIR), allows us to control the cavity length, and therefore, the repetition rate. The shorter this waveguide is, the shorter the cavity and the higher the repetition rate. On each side, a 2x0 MIR reflector defines the resonator and provides optical output. We have used the same type of MIR reflector on both ends in order to ensure symmetry around the SA, as this is a critical aspect in CPM to ensure the best quality for the generated optical pulses [1].

![Diagram of the device structure](image)

Fig. 1. On-chip colliding mode locked lasers based on multimode interference reflectors: (a) Schematic of the device structure, and (b) Microscope photograph of different devices, with different cavity lengths, fabricated in the MPW run.

The MIR mirror structures derive from a standard multimode interference (MMI) coupler [16], in which deeply etched 45° mirrors at suitable locations reflect back the light by total internal reflection. The length and width of the MIR mirror are 90.3 μm and 6 μm respectively [18]. There are two types of MIRs depending on the number of ports in the MMI. One has a single port (1x0 MIR), and is based on a 1x2 MMI coupler to offer a 100% light reflection. An alternate design is based on a 2x2 MIR coupler, defining the 2x0 MIR reflector. This option has two access ports, so that the light entering into one of these ports is divided evenly and reflected back to the two ports. This offers a 50% reflection mirror with an output. For the sake of symmetry, we have used 2x0 MIR reflectors on both ends of the device, having access to the optical output on each side. The output is directed to the chip cleaved edges for analysis. In order to reduce back-reflections at the edges, the output waveguides were angled 7° to the chip edge and anti-reflection (AR) coating was used at the facets.

A microscope photograph of device samples is shown in Fig. 1(b), where three on-chip laser devices can be seen. The top and bottom devices are OCCP-MLLD structures, where the SA contact is visible at the center of the cavity. The different elements in the resonator are clearly visible, showing the symmetry around the SA. At the center, a Fabry-Perot cavity laser was included for other studies. The two colliding pulse mode-locked laser structures were designed with different cavity lengths. Both devices have the same active region length, fixed to 800 μm. The lengths of the two SOAs add up to 780 μm, separated by a 20 μm SA at the
The first one (Dev_A), shown at the top in Fig. 1(b), was designed for a fundamental repetition rate of 18.47 GHz. In the colliding regime (when the repetition rate doubles), the frequency would be 36.94 GHz. The advantage of this frequency is that it is in the millimeter-wave range (usually defined between 30 to 300 GHz) and still remains within the range of our electrical spectrum analyzer, an Anritsu MS2668C that covers from 9 KHz to 40 GHz. This avoids the requirement of external mixer heads, which introduce losses in excess of 30 dB, to characterize the signals. An additional device (Dev_B), shown at the bottom of Fig. 1(b), was included with a cavity length that is about half the cavity length of Dev_A. This device allows us directly generate signals in the 60-90 GHz range, currently being proposed for wireless communications. Table 1 summarizes the features of both devices developed in the MPW run, where the lengths of both the components are shown with their respective fundamental frequency (FF) and second harmonic frequency (SHF).

<table>
<thead>
<tr>
<th>Devices</th>
<th>Components Length (um)</th>
<th>Repetition Rate (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIR  SOA  SA  PW  L_cav</td>
<td>FF     SHF</td>
</tr>
<tr>
<td>Dev_A</td>
<td>90.3  780  20  129.4  2210</td>
<td>18.47  36.94</td>
</tr>
<tr>
<td>Dev_B</td>
<td>90.3  780  20  253.4  1234</td>
<td>34.88  69.76</td>
</tr>
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</table>

3. Characterization

The setup that we have used to characterize the chip is sketched in Fig. 2. The device is mounted on a copper chuck that was temperature stabilized to 16 °C. The electrical access was provided through DC needle probes. The current into the two SOA sections was supplied from a single ILX 3724B laser diode controller, while the reverse bias into the SA was provided by an Agilent E3631A voltage source. The optical output from the angled facet of the OCCP-MLLD was collected using anti-reflection coated lensed fibers, including an optical isolator (OI). This element was followed by a 90/10 splitter which divided the light in two branches. The 10% branch is connected to a Newport 842-PE power meter (PM), providing a constant measure of the generated optical power. The other branch, with 90% split, is used to characterize the device using different instruments. The optical characterization includes a Yokogawa AQ6370B optical spectrum analyzer (OSA), to observe the optical spectrum. Also, after being amplified on a Nortel FA14UFAC telecom erbium doped fiber amplifier (EDFA), an APE pulse-check auto-correlator (AC) to measure the pulse autocorrelation. For the electrical characterization of the RF beat signal we used a 90 GHz −3-dB bandwidth U2T XPDV4120R photodiode (PD) to perform the optoelectronic conversion. Depending on the frequency range, we have external mixers which down-convert the signal frequency. For Dev_B, we used the mixer from Anritsu, MA2744A (50 GHz - 75 GHz).

The output light power versus current injection (P-I) curve of the two devices is shown in Fig. 3. Where Fig. 3(a) and Fig. 3(b) show the P-I curve for Dev_A and Dev_B respectively when a fixed SA reverse voltage $V_{SA} = -1.7$ V is applied. We can clearly observe that the threshold current for Dev_A is 64 mA, while for Dev_B, we measured 35 mA. Due to the fact that both devices use the same building blocks, and that the only difference between them is the length of the passive waveguide, this difference must be attributed to passive waveguide propagation losses. Thanks to the 90/10 coupler, while measuring the optical power, we also measured the optical spectrum. The evolution of the optical spectrum with current injection for each of the two devices, under the same reverse bias condition $V_{SA} = -1.7$ V, are shown in Fig. 3(c) for Dev_A and Fig. 3(d) for Dev_B. We clearly identify on both devices an initial regime of operation, continuous wave (CW), in which different Fabry-Perot modes start lasing, followed by the onset of stable mode locking, in which the optical spectrum takes a Gaussian distribution. In Dev_A, the range of currents with mode locking (ML) goes from 72
mA to 100 mA (which is the maximum current injected into the device), while Dev_B from 52 mA to 100 mA, the device enters into a colliding pulse mode-locked state.


Fig. 3. Optical power versus injection current (P-I curve) for: (a) Dev_A and (b) Dev_B. Identified regions are CW: continuous-wave, ML: mode-locked. Evolution of optical spectrum: (c) Dev_A and (d) Dev_B. Detailed P-I curve around threshold at different SA voltages for: (e) Dev_A and (f) Dev_B.

Focusing around the threshold current level, we performed detailed measurements of the P-I curve at different voltage levels on the SA (with $V_{SA} = 0 \, V$, $-1 \, V$, $-1.7 \, V$ and $-2 \, V$). As shown in Fig. 3(e) and Fig. 3(f), we do not observe sharp jumps of the optical power nor have we measured any hysteresis on any of the devices. The appearance of hysteresis has been reported in quantum dot [25] and quantum well [26] gain material devices, usually linked to high reverse bias voltages on devices with large SA sections, with gain-to-absorber length ratios of 7:1 and 14:1 respectively, while in our case this ratio is 40:1. The short SA was designed following previous CPM observations which showed a reduction in the pulse...
duration as the absorber width is reduced [1]. We can therefore conclude that hysteresis is not observed due to the relatively short SA (20 μm) to the gain section length (800 μm) and the low reverse bias voltages from 0 to −3.5 V. These levels were used to avoid generating a high photocurrent level at the absorber.

To characterize in detail the colliding mode-locked regime, we have selected a bias point exhibiting this behavior, at a gain section current $I_{SOA} = 80$ mA and SA reverse biased $V_{SA} = −1.7$ V. The optical spectrum for Dev_A is shown in log and linear scales in Fig. 4(a) and Fig. 4(b) respectively. The emission wavelength is 1562 nm, and the full-width half-maximum (FWHM) is $Δv = 3.244$ nm (404.8 GHz). The inset in Fig. 4(a) shows a detail of the optical mode spectrum, side mode suppression ratio (SMSR) between the fundamental mode spacing (18.47 GHz) to the colliding mode spacing (36.94 GHz) is 22 dB. For Dev_B, the log and linear scale optical spectrums are shown in Fig. 4(c) and Fig. 4(d) respectively in same bias conditions ($I_{SOA} = 80$ mA, $V_{SA} = −1.7$ V). The device has the same emission wavelength range, around 1562 nm, with FWHM $Δv = 2.771$ nm (345.8 GHz), slightly narrower than the previous one. At the inset in Fig. 4(c) we observe that the SMSR between the modes spaced at the fundamental frequency to those spaced at the colliding frequency spacing is similar, 24 dB, despite the higher repetition rate.

The electrical characterization of the generated RF beat note was performed using a 90 GHz bandwidth PIN photodiode connected to a 40 GHz electrical spectrum analyzer. For this reason, we focused the electrical analysis on Dev_A, which has a colliding repetition rate frequency within this range, comparing different operating conditions.

First, we analyze the electrical spectrum at the same gain current level that we used for the optical spectrum, setting gain section at $I_{SOA} = 80$ mA. Figure 5 shows the results when the saturable absorber is not biased ($V_{SA} = 0$ V). Figure 5(a) shows the full span of the electrical mode beating spectrum. In this condition, peaks at the fundamental (FF = 18.47 GHz) and second harmonic (SHF = 36.94 GHz) frequencies are visible. As shown in Fig. 5(b) the two electrical frequencies are maintained as the current increases from 40 mA (close to the

![Fig. 4. (a) Optical spectrum log scale of the Dev_A. The inset shows the frequency mode spacing of 36.94 GHz, resolution 0.02 nm. (b) Optical spectrum linear scale of the Dev_A. (c) Optical spectrum log scale of the Dev_B. The inset shows the frequency mode spacing of 69.76 GHz, resolution 0.02 nm. (d) Optical spectrum linear scale of the Dev_B.](image-url)
threshold) to 100 mA (the maximum injected current) exhibiting slight variations of the order of 240 MHz for the FF and 160 MHz for the SHF. It is worth noticing that the shift of the colliding frequency (SHF) is smaller than that of the fundamental. This is in agreement with the general observation that colliding pulse mode-locked structures are more stable than fundamental mode locking ones [1]. In Fig. 5(c) and Fig. 5(d) we show the electrical beat note linewidth (dotted blue line) and its fit to a lorentzian line-shape (continuous red line) for the FF and SHF respectively. From Fig. 5(c), the linewidth of the fundamental frequency is $\Delta v_{RF} = 15.41$ MHz and from Fig. 5(d), the linewidth of the second harmonic is $\Delta v_{RF2} = 1.17$ MHz. We observe that the linewidth of the second harmonic frequency is smaller, and assume that is due to the colliding pulse mode-locked (CPM) structure of the device [1].

![Fig. 5. (a) Electrical spectrum of the Dev_A at free running condition, CF = 20 GHz, span = 40 GHz, RBW = 3 MHz, VBW = 3 MHz. (b) Electrical spectra map of the Dev_A at $V_{SA} = 0$ V. (c) Fundamental frequency linewidth of the Dev_A, CF = 18.473 GHz, span = 500 MHz, RBW = 1 MHz, VBW = 1 MHz. (d) Second harmonic frequency linewidth of the Dev_A, CF = 36.946 GHz, span = 90 MHz, RBW = 1 MHz, VBW = 1 MHz.](image)

We now present the electrical mode beating spectrum in a colliding pulse mode locked condition, keeping the gain section at $I_{SOA} = 80$ mA, setting the SA at $V_{SA} = -1.7$ V. As shown in Fig. 6(a), presenting the full span, the only peak present in the spectrum appears at the second harmonic (SHF = 36.94 GHz). Figure 6(b) shows that this is the case for the entire range of variation of the gain section current (from 40 mA to 100 mA), where the fundamental frequency appears over a small range from 70 to 79 mA, after which it disappears. In this regime, we also observe a reduction in the SHF shift with current, down to 80 MHz for a current change from 68 mA to 100 mA. The detailed trace of the colliding RF beat signal is shown in Fig. 6(c), using blue circles for the experimental data, and a continuous red line for the lorentzian line-shape fit. The linewidth of this frequency tone is $\Delta v_{RF2} = 343$ KHz, one order of magnitude smaller than the one achieved with no reverse bias voltage in the SA. We can therefore highlight the stability of the colliding regime of these novel devices.

For the sake of comparison we present in Fig. 7(a) the electrical mode beating spectrum of Dev_B, when the device is biased in a colliding regime using the same conditions ($I_{SOA} = 80$ mA, $V_{SA} = -1.7$ V). This measurement required the use of external multiplication head Anritsu MA2744A (50 GHz - 75 GHz) to down-convert the repetition rate frequency of the signal (69.76 GHz) to the input range of the electrical spectrum analyzer. The linewidth of this tone is $\Delta v_{RF2} = 1.91$ MHz and is shown in Fig. 7(b).
Fig. 6. Electrical spectrum of the Dev_A at a colliding pulse mode locking regime: (a) full span, (b) Electrical spectrum evolution at $V_{SA} = -1.7$ V and (c) Colliding beat note linewidth.

Fig. 7. Electrical spectrum of the Dev_B at a colliding pulse mode locking regime: (a) Span = 500 MHz, (b) Colliding beat note linewidth.

The pulse characterization is performed using a background-free APE Pulse-Check autocorrelator. The pulse widths for Dev_A were measured under various conditions in order to analyze the evolution of the pulse width with gain section current and SA reverse voltage. We have first measured the pulse width as the injection current ($I_{SOA}$) is varied from 60 mA to 120 mA while the reverse voltage at the saturable absorber SA ($V_{SA}$) remains fixed at $V_{SA} = -1.7$ V. The evolution of the pulse width versus gain section current level is shown in Fig. 8(a), in which, the pulse width data is represented by blue circles and is fitted to a linear curve (red, continuous line). In the same figure, we introduce the results about the time bandwidth product (TBP), representing the measured data with blue squares, which are fitted to a linear trace (black, continuous line) is depicted simultaneously. We demonstrate the linear dependence between the pulse width (and TBP) with the current injection level into the gain section.

We have also analyzed in Dev_A the dependence of the pulse width with varying reverse voltage in the SA ($V_{SA}$) from $-1.5$ V to $-3$ V at a fixed injection current level at $I_{SOA} = 80$ mA. Figure 8(b) represents the measured pulse width data versus reverse voltage levels using blue dots, which are fitted to an exponential trace (red, continuous line). The time bandwidth product (TBP) data is also included with blue squares, fitted to a linear curve (black, continuous line). We observe the exponential dependence of the pulse width with the reverse SA voltage. We would like to highlight that appreciate the same trends as reported in other
mode-locked structures, showing pulse broadening with increasing injection current usually attributed to self-phase modulation (SPM) and shortening with increasing absorber reverse voltage due to absorber recovery time reduction [26]. The shortest pulse-width that we have achieved, assuming an hyperbolic secant pulse shape, is $\Delta \tau = 0.64$ ps, when the absorber is biased at $V_{\text{SA}} = -3.0$ V and gain section to $I_{\text{SOA}} = 80$ mA. Figure 8(c) shows the autocorrelation trace of the shortest pulse. The time bandwidth product (TBP) obtained was TBP = 0.39, closed to the Fourier transform limit 0.3148 [27].

The noise performance of the Dev_A was evaluated in order to quantify the stability of the colliding pulse mode-locked regime, when the gain section is biased at $I_{\text{SOA}} = 80$ mA and the SA is biased at $V_{\text{SA}} = -1.7$ V. We measured the phase noise, which calculates the stability of the generated signal frequency and the amplitude noise which quantifies the variation of a pulse peak level from the average value. The phase noise allows defining the timing jitter which provides the stability in terms of femto seconds. Using the Von der Linde method, the timing jitter can be extracted from the integration of the side bands over a frequency range [28] while the amplitude noise is defined by the integration of the relative intensity noise [23]. It is common to use the ITU-recommended integration ranges defined by viable clock recovery techniques [29], in order to define the timing jitter and the amplitude noise. The noise evaluation was extracted from the integration range [4–80 MHz] which is used to define the amplitude noise and the phase noise [21]. Figure 9(a) depicts the single side-band phase noise (SSB - $L(f)$) of the Dev_A, the obtained timing jitter is $\sigma_T = 75$ fs, integration range [4–80 MHz] and Fig. 9(b) shows the recording of the amplitude noise measurement of the Dev_A, where we were able to determine the amplitude noise $N_{\text{AM}} = 0.012$ dBC (< 0.036%), integration range [4 – 80 MHz].

Table 2 summarizes all the measurements performed in the devices that were fabricated in the Smart Photonic multi-project wafer (MPW) run by using the same methodology of bias conditions ($I_{\text{SOA}}$ and $V_{\text{SA}}$) for the characterization of the devices. For both devices, the gain
section is biased at $I_{SOA} = 80$ mA, the saturable absorber is reverse biased at $V_{SA} = -1.7$ V and the temperature is stabilized at 16 °C by a thermoelectric cooler (TEC) and thermistor. The collected parameters provide the values of the fundamental frequency (FF), second harmonic frequency (SHF), spectral width ($\Delta v$), second harmonic beating linewidth ($\Delta v_{RF2}$), shortest pulse width ($\Delta \tau$), time bandwidth product (TBP), lowest timing jitter ($\sigma_T$) and amplitude noise ($N_{AM}$). From the comparison of the parameters among the samples that were fabricated in the SMART Photonics multi-project wafer run, we have experimentally demonstrated the shortest pulse width $\Delta \tau = 0.64$ ps, with low timing jitter $\sigma_T = 75$ fs and amplitude noise $N_{AM} = 0.012$ dBC.

Table 2. Measurements performed in the devices fabricated in SMART Photonics MPW run.

<table>
<thead>
<tr>
<th>Devices</th>
<th>FF (GHz)</th>
<th>SHF (GHz)</th>
<th>$\Delta v$ (GHz)</th>
<th>$\Delta v_{RF2}$ (KHz)</th>
<th>$\Delta \tau$ (ps)</th>
<th>TBP</th>
<th>$\sigma_T$ (fs)</th>
<th>$N_{AM}$ (dBC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dev_A</td>
<td>18.47</td>
<td>36.94</td>
<td>404.8</td>
<td>343</td>
<td>0.64</td>
<td>0.39</td>
<td>75</td>
<td>0.012</td>
</tr>
<tr>
<td>Dev_B</td>
<td>34.88</td>
<td>69.76</td>
<td>345.8</td>
<td>391</td>
<td>0.66</td>
<td>0.37</td>
<td>89</td>
<td>0.027</td>
</tr>
</tbody>
</table>

4. Conclusion

In conclusion, we present a novel on-chip colliding pulse mode-locked laser diode structure which uses multimode interference reflectors to define the cavity. These mirrors allow to precisely position the SA location in the cavity, achieving the colliding pulse mode-locked regime. This device is a versatile source for high quality generation of ultra-short optical pulses at millimeter wave frequency repetition rates (30 to 300 GHz). Measurements have shown sub-picosecond pulses close to the Fourier transform limit, with pulse widths as short as $\Delta \tau = 0.64$ ps with low timing jitter, $\sigma_T = 75$ fs, and amplitude noise $N_{AM} = 0.012$ dBC. The devices have been fabricated in a multi-project wafer service, using an active/passive technology generic foundry which reduces costs.

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