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Photonic Integrated Fully Tunable Comb Generator Cascading Optical Modulators

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***Abstract*—We report the first monolithic InP photonic integrated comb generator made by cascading optical modulators. The device is extremely compact and tunable both in repetition frequency and wavelength, making real-world applications possible. A distributed Bragg reflector laser, a Mach–Zehnder intensity modulator, and two phase modulators are monolithically integrated on a 4.5 × 2.5 mm^2 chip that also includes a booster semiconductor optical amplifier at the output. Modulators integrated on the circuit have a 3 dB bandwidth of 7 GHz and can generate up to 28 comb lines within a 5 dB power range when properly electrically driven (here demonstrated in the range 4–5 GHz). Operation up to 10 GHz is also reported.**

***Index Terms*—Comb generation, InP monolithic photonic integration.**

I. Introduction

OPTICAL Frequency Comb Generators (OFCGs) are optical subsystems largely studied for a range of applications including metrology [1], [2], spectroscopy [3], [4], optical communications [5], THz generation [6], optical arbitrary waveform generation [7] and microwave photonics [8]. The OFCG required performance depends on the application, but compactness and correlation between the optical lines are always needed. For this reason, in order to take this technology out of the laboratory to meet real applications, compact systems are needed for replacing bulky implementations. To this aim, various compact devices have been investigated for OFCG implementation including pulsed optical sources such as Mode-Locking Laser Diodes (MLLDs) [9], microresonators [10], or semiconductor gain switched laser diodes, including vertical cavity surface emitting lasers (VCSELs) [11]. These devices can be classified according to their repetition frequency, being MLLDs and gain switched lasers in the order of several GHz, microresonators in the order of few hundreds of GHz.

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Microresonators are promising devices able to generate extremely wide OFCGs, but their high repetition frequencies make them unsuitable for a significant number of applications. On the other hand, MLLDs miss any continuous tunability of the repetition frequency and need specially designed structures. Finally, gain switched laser diodes are interesting compact devices, but they offer optical spans limited to hundreds of GHz. An alternative flexible solution for the generation of coherent combs is the use of a cascade of optical modulators with synchronous electrical sinusoidal modulating signals [12]. This scheme allows the generation of stable and high power optical combs with tunable frequency separation (typically as large as the modulator bandwidth), but requires a bulk and complex setup including a monochromatic laser and a certain number of phase and intensity modulators depending on the required number of comb lines.

In this paper, we report, to best of our knowledge, the first photonic integrated implementation of such a promising scheme. Photonic integration allows at the same time for miniaturization of the scheme and large reduction of both optical losses and power consumption. This enables its use in out-of-the-lab real world applications.

A preliminary characterization of a similar integrated circuit has been recently reported [13]. In respect of that report, here we show a modified circuit, which also includes an input waveguide to inject light from an external laser source (as an alternative to the on-chip laser), and demonstrate that a larger number of comb lines is attainable by using larger voltage swings to drive the integrated optical phase modulators.

II. Integrated Comb Generator Description

The integrated comb generator based on a cascade of modulators is sketched in Fig. 1(a) and 1(b). The continuous-wave (CW) seed optical signal can be either provided externally thanks to a proper input waveguide terminated with a spot size converter (SSC), or obtained on chip by a tunable distributed Bragg reflector laser diode (DBR-LD), integrated in the chip, working at a selectable wavelength in the C band. The signal then crosses a Mach-Zehnder modulator (MZM) realized by means of a 1 × 2 multi-mode interference device (MMI) used as a splitter, two 1-mm-long phase modulators (PM) and a 2 × 1 MMI used as a coupler. After propagating through the MZM, the signal crosses a series of two further 1-mm-long PM. Finally, the modulated signal is amplified in a 0.5-mm-long multi quantum-well semiconductor optical amplifier (SOA) and reaches the PIC

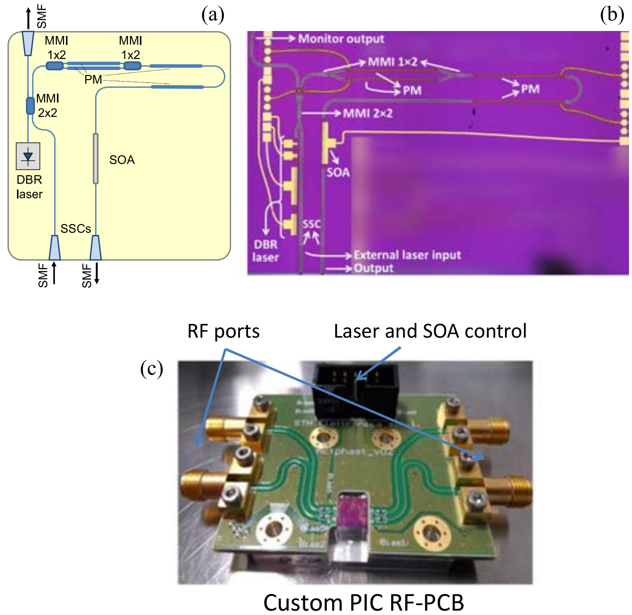

Fig. 1. (a) Integrated comb regenerator PIC schematic. (b) Picture of the fabricated PIC (Footprint: 4.5 × 2.5 mm^2). (c) PIC-PCB assembly.

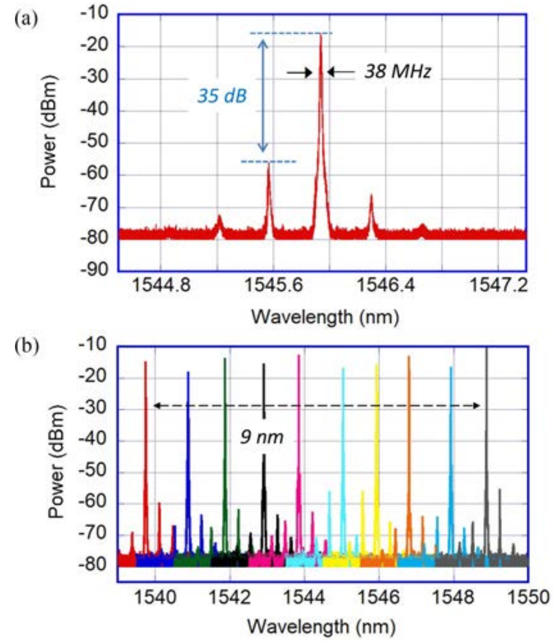

Fig. 2. (a) DBR-LD emission spectrum. (b) Tunability characterization. Resolution = 20 MHz (0.16 pm).

output facet through an additional SSC to optimize the coupling efficiency with an optical fiber. To reduce back-reflections into the chip, anti-reflective coating has been added on the facets. Bare chip testing is enabled through electrical multiprobes landing on arrays of square and round metal pads (for DC and RF contacts respectively).

The InP PIC has been fabricated by Oclaro Technology plc, UK, in a multi-project wafer run [14]. The footprint of the integrated comb generator, shown in Fig. 1(b), is around 4.5 × 2.5 mm^2, limited by the placement constraint of phase modulators and gain sections, required to be orthogonal with respect to each other. Devices on-chip are connected by means of deeply-etched passive waveguides with a width of 1.5 μm, characterized by a loss of about 5 dB/cm. The DBR-LD is made up of two DBR grating mirrors with a pitch of 237.5 nm: the length of the back mirror is 250 μm, while, the length of the front mirror is 30 μm. Between the two mirrors a 450-μm-long gain section and a 50-μm-long phase tuning section are present. Wavelength tunability in the laser emission is achieved by varying the current injected into the mirrors and the phase tuning section.

The InP chip was attached on a metal base using a thermal and electrical conductive epoxy, and then wire bonded to a custom-built PCB, as shown in Fig. 1(c). Four RF ports were used to drive the PM, while 5 DC ports were needed to control the DBR sections and the SOA. The back of the chip was connected to ground through the metal base. The temperature was controlled by means of a thermo-electric cooler (TEC) placed below the base and standing on a heat sink. The optical input/output of the chip was obtained by means of tapered single fibers or an array of two fibers. Power consumption of the optical chip was less than 0.5 W, while the overall power consumption of the comb generator depends on the arrangement of the TEC in the PIC mounting/packaging and on the specific electrical drivers used.

III. Experimental Characterization

In this section, we report the characterization of the devices comprising the integrated comb generator. To test the laser source, we used a test output of DBR-LD connected to a SSC on the opposite side of the chip in respect of the input/output ports, as shown in Fig. 1(a), and a tapered fiber to probe the output power level and spectrum. The SSC to fiber loss has been measured to be 5 dB. Fig. 2(a) and 2(b) report respectively the DBR-LD emission spectrum at a single wavelength and for different tuning conditions. As shown in Fig. 2(a), the LD has a monochromatic emission with typically 35 dB side mode suppression ratio (SMSR) and 38 MHz linewidth, as measured directly with heterodyne optical spectrum analyzer.

The output power is 13 dBm. Tunability is 9 nm, the operating wavelengths were different for various chips and were in the range 1539–1558 nm.

To assess the performance of the PMs positioned in the MZM branches and at the MZM output we used a test MZM identical to the one in the comb generator: as reported in Fig. 3(a), at $V_{\mathrm{bias}} = -7$ V, we measured a static extinction ratio of 25 dB and a $V\pi \sim 5$ V.

The frequency response of the modulator was measured by applying the signal from a vector network analyzer to the PM on each arm of a test MZM connected to a photodiode and measuring the resulting current. Fig. 3(b) shows the normalized s_{21} parameter, where the 3 dB-bandwidth is limited to 7 GHz due to the lumped electrical contacts and the lack of any 50 Ohm termination on chip.

As it can be noticed, because of the typical non linear behavior of the quantum confined Stark effect based phase modulators, the MZM transfer function is not periodic and shows an exponential-like attenuation. This limits the voltage swing that

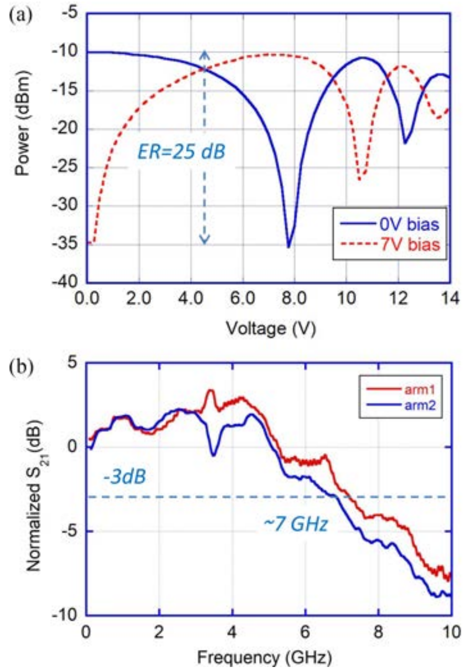

Fig. 3. (a) MZM static characteristics. (b) PM bandwidth measurements.

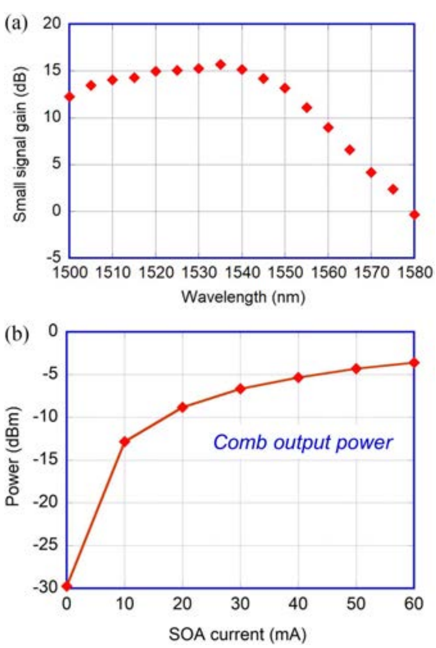

Fig. 4. (a) SOA small signal gain. (b) SOA output power as a function of the bias current.

can be applied to the phase modulators to have comb line multiplication, and, as a consequence, limits the number of attainable comb lines and the comb flatness.

As shown in Fig. 1, the output signal is boosted by a 0.5-mm-long SOA. For characterization purposes an identical SOA was exploited having both ports connected to SSCs. Fig. 4(a) and 4(b) show the SOA small signal gain and output power as a function of the signal wavelength and the bias current, respectively. From Fig. 4(a), we have a 62 nm 3-dB bandwidth centered at 1535 nm for the small signal gain (injected input power -8 dBm to avoid gain saturation and SOA bias current fixed at 60 mA). The maximum output power, reported in Fig. 4(b), measured during comb operation at 60 mA bias current is -4 dBm.

IV. Comb Generation

Comb generation by the PIC has been tested using the experimental setup reported in Fig. 5. Synchronous modulation is obtained by means of a low noise sinusoidal signal generator, this signal was then split in four and crossed four different RF phase shifter used as delay lines. The signals were then amplified by electrical drivers and coupled to the bias voltages through four high bandwidth Bias-tees. The DBR laser and the SOA were controlled by means of laser drivers connected to the PIC through a multiple pin interface on the PCB). All measurements have been performed at 25 °C. A single fiber output by a tapered fiber or a double input/output fiber connection through the use of a fiber array were available.

The following analyzers have been used in the comb characterization:

- for optical spectra: Apex AP2440A Optical Complex Spectrum Analyzer (resolution: 20 MHz).
- for electro-optic bandwidth measurements: Agilent N5230 10-MHz-50 GHz PNA-L Network Analyzer.
- for phase noise measurements: Agilent E5052A Signal Source Analyzer with option E5053A with 10 MHz-26.5 GHz bandwidth.

Examples of the attainable optical combs are reported in Fig. 6(a) and 6(b) at 4 and 10 GHz respectively.

To obtain a larger comb line count and enhanced comb flatness the phase modulators must be driven with multi-Vπ voltages and the MZM with around Vπ voltages [12]. From Fig. 3, we see that around 13 V_{pp} are required to have 3 Vπ. However, in our case, voltage swings are limited by available components: we could use electrical driver amplifiers working at 4–5 GHz having 11 V_{pp} output voltage and broadband amplifiers (0–12 GHz) with 6.3 V_{pp} output.

Fig. 6(a) shows a 4 GHz comb obtained using the following driving conditions: the MZM branches were biased at $V_{MZM} = -10$ V and the PMs at $V_{PM} = -11$ V, driving voltages were 6.3 V_{pp} for the MZM and 11 V_{pp} for the PMs. The DBR-LD and SOA were biased with $I_{LD} = 85$ mA and $I_{SOA} = 60$ mA, respectively. The comb is centered at 193.02 THz (1553.2 nm) and shows 28 lines within 5 dB power ratio from the maximum of the comb. Similar spectra are obtained in the amplifiers operating in the range 4–5 GHz.

Fig. 6(b) shows a 10 GHz comb obtained using the same DBR and SOA operating conditions and 6.3 V_{pp} driving voltages for all the modulators. In this case, because of limited driving voltages to the PMs and bandwidth limitations of the unmatched modulators (see Fig. 3(b)), 11 comb lines are visible in a 10 dB power range. Nevertheless, a larger line count is expected by proper chip electrical line load matching and larger driving voltages.

The spectral purity of the optical combs generated by our PIC has been also characterized by using a signal source analyzer as

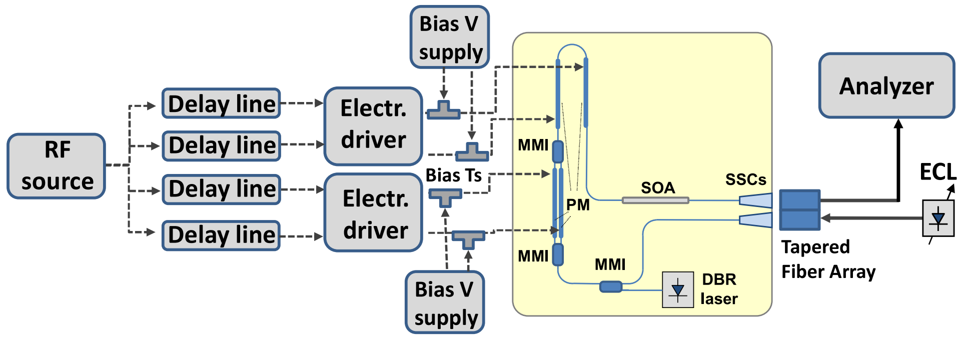

Fig. 5. Experimental setup for comb generation test.

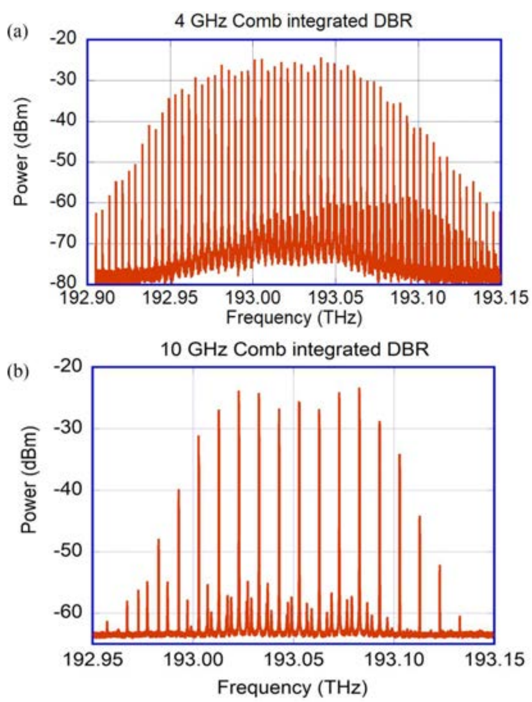

Fig. 6. (a) 4 GHz comb generation with optimal electrical driving voltages. (b) 10 GHz comb generation with suboptimal driving voltages. Res. = 20 MHz.

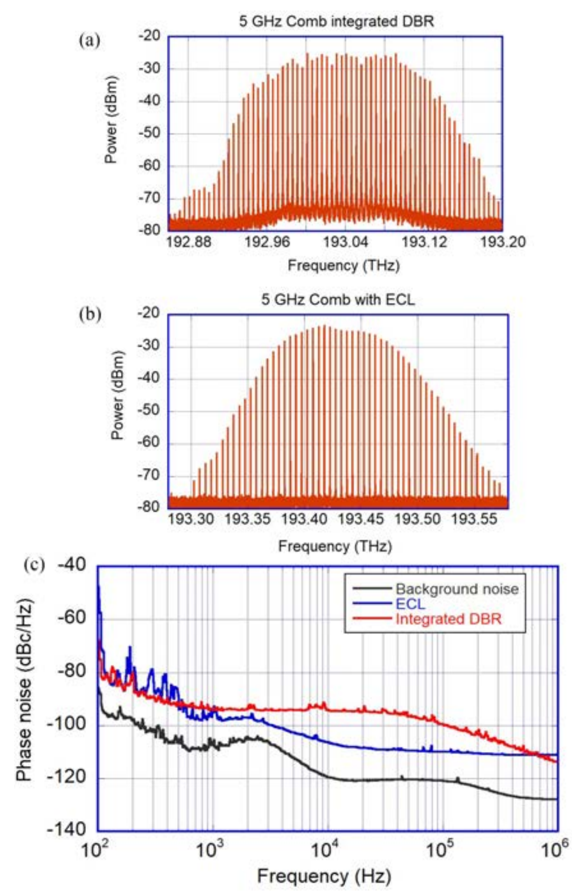

Fig. 7. (a) 5 GHz comb generation with optimal electrical driving voltages using the on-chip DBR. (b) 5 GHz comb generation with optimal electrical driving voltages using an off-chip ECL. (c) Phase noise comparison.

reported in Fig. 7. A comb with 5 GHz repetition rate has been generated using similar driving condition like in the 4 GHz case (reported in Fig. 7(a)), and an additional 5 GHz comb (reported in Fig. 7(b)) has been obtained by using an input CW signal generated by an external cavity laser (ECL) instead of the on-chip DBR. The external light is injected in the PIC by using the input optical port shown in Fig. 1(a), employing in this case an array of 2 fibers for optical I/O. This last spectrum appears cleaner showing less noise at low power levels, mostly because of a much larger SMSR and smaller linewidth. This is confirmed by the phase noise characterization performed on the second comb tone at 10 GHz and reported in Fig. 7(c). From there we find that, while very low frequency phase noise up to 1 kHz is comparable or even lower with the on-chip DBR, a larger phase noise is evident at larger frequencies. This fact is correspondent to the larger DBR CW linewidth. In particular, there is a gain of around 10 dBc/Hz in the range 10-100 kHz by using an out of chip ECL.

V. Conclusion and Discussion

The compact photonic integrated realization of a tunable optical comb generator based on the cascade of optical modulators is reported for the first time. The InP PIC integrates, in a chip of around 4.5×2.5 mm^2, a DBR laser, a Mach-Zehnder modulator, two phase modulators and a booster semiconductor optical amplifier. The PIC has been mounted on a custom PCB and tested up to 10 GHz operation, showing that, when properly driven (in the range 4–5 GHz repetition rate in our case), it can generate up to 28 comb lines in a 5 dB power range.

Typical bandwidth of the modulators is 7 GHz due to the lumped geometry and to the lack of any impedance matching for the electrical contacts. A larger operating bandwidth can be expected by including a proper off-chip load or using InP modulators with optimized structure and travelling wave or segmented electrical contacts. In this last case operation up to 50 GHz frequency is possible [15], so that an InP broadband integrated comb working in the 0–50 GHz range or more is possible with our design.

Phase noise measurements reported in the previous section shows that the PIC can be used employing the on-chip tunable laser or, alternatively, an external CW laser. This gives the flexibility to use a spectrally pure out-of-chip seed laser in case the specific application requires phase noise characteristics that cannot addressed with the on-chip laser.

In addition, it should be considered that more complex electrical driving schemes can be exploited in order to further enhance the number of usable comb lines [16].

In conclusion, we demonstrated the first fully tunable (in wavelength and repetition frequency) monolithically integrated comb generator made cascading optical modulators driven by synchronous sinusoidal signals. This makes possible out-of-the-lab use of such a flexible scheme for real world applications in spectroscopy, optical communications, THz generation and optical arbitrary waveform generation.

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