Millimeter and Sub-terahertz wave Generation with an On-chip Colliding Pulse Mode-Locked Laser Diode.

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Abstract— **We report the generation of millimeter and sub-terahertz waves with an on-chip colliding pulse mode-locked laser diode (OCCP-MLLD) by using two different approaches. The first approach is the pulsed source method based on an OCCP-MLLD structure that allows on-chip integration using multimode interference reflectors (MIRs). The OCCP-MLLD is capable of generating a carrier at 70 GHz due to the colliding pulse mode locking regime. The second approach is the optical heterodyning method using an on-chip colliding pulse mode-locked laser with an arrayed waveguide grating optical filter (OCCP-AWG). The OCCP-AWG provides a carrier at 90 GHz by filtering two optical modes.**

I. INTRODUCTION

Over recent decades, data rates in both fibre-optic and wireless communications have been increasing exponentially so modern technology roadmaps point to the need of increasing the data rates used into the multi-gigabit-per-second to cope with the future needs based in current trends of the demand [1]. Latest researches are focused in the high millimetre-wave and sub-terahertz region due to high carrier frequencies promise unprecedented channel capacities [2]. As a result, a current cost effective solution is to increase the carrier wave frequency into the millimeter wave region, moving to the E-band (60 to 90 GHz) and beyond [3]. The difficulties to generate, amplify and modulate signals at these frequencies have been overcome by combining electronic with photonic techniques. Currently, most if not all of the reported wireless communication systems operating above 100 GHz employ photonic generation of the carrier frequency, demonstrating different available techniques [4].

Photonic integrated circuits (PICs) allow addressing the main challenges like size and cost. Therefore, PICs have as key advantage enabling the integration of multiple photonic building blocks within a single chip, reducing the number of fiber couplings that are necessary to interconnect them, developing compact systems with increased functionality and performance [5].

The generation of stable signals over a wide range of frequencies is carried out by two outstanding methods. They are the pulsed source and the optical heterodyning methods [6]. In one hand, the pulsed source method uses a mode locked laser diode (MLLD) for signal generation. The optical modes of the MLLD which are locked in phase are mixed into a photodiode in order to obtain the electrical beating frequency. The efficiency of the optical to millimeter-wave transduction is high, ideally 100%, the range of frequencies that can be generated is very large, limited by the bandwidth of the photo detector. On the other hand, the optical heterodyne method requires an optical signal source generating two different wavelengths that are mixed into a photodiode or photoconductor or another type of opto-electronic transducer. The generated signal is an electrical beat-note at a frequency given by the difference between the two wavelengths. Mode locked laser diodes have successfully been used in photonically enabled wireless link demonstrations operating in the millimeter wave range to generate carrier frequencies at 60 GHz [7] and 120 GHz [8]. While the former employs the pulsed source method by using a self-pulsating MLLD with a repetition rate equal to the desired carrier frequency, the latter works with the optical heterodyning method by using a MLLD operating at 60 GHz and an arrayed waveguide grating (AWG) in order to select two modes from the MLLD optical spectrum with the intention of generating a 120 GHz carrier. On both approaches, fiber optic components were used to process the MLLD output.

The main objective of this work is to present two different approaches of photonic integrated circuits for millimeter-wave and sub-terahertz wave signal generation. The first approach is the pulsed source method which is based on a novel on-chip colliding pulse mode-locked (OCCP-MLLD) laser structure that employs multimode interference reflectors (MIRs), which is capable of generating a carrier at 70 GHz. The other approach is the optical heterodyning method which is founded on the implementation on a single chip of a novel OCCP-MLLD, followed by an AWG to filter two optical modes. In this type of approach, the pulse repetition rate must be a sub-harmonic of the AWG channel spacing. The devices have been fabricated within a commercial multi-project wafer (MPW) run available through SMART Photonics InP active-passive integration foundry service [9].

II. ON-CHIP PHOTONIC INTEGRATED CIRCUIT STRUCTURES

As we detailed earlier, the photonic based generation of signals with frequencies within the millimeter and sub-terahertz ranges is allowed by pulsed source and the heterodyning methods. In one hand, the pulsed source method which is composed by a single optical source and a photomixer (photodiode or photoconductor, PD) is shown in Fig. 1(a). The single optical source is a comb generator like a mode locked laser, which provides a comb of phase locked narrow linewidth modes with a fix frequency spacing. On the other hand, the optical heterodyning method composed by an optical comb, optical filter, optical combiner and a photomixer is shown in Fig. 1(b). In the heterodyning method, two optical modes are selected from the optical comb. Then, the two optical modes are combined an injected into a photomixer.

We present novel implementations using MIR reflectors to replace the cleaved facets for the mirrors at both sides of the Fabry-Perot cavity with the intention of develop an on-chip photonic integrated structure. MIR reflector structures derive from a standard multimode interference (MMI) coupler, in which deeply etched 45° mirrors at proper locations reflect back the light by total internal reflection. The length and width of the MIR mirror are LMIR = 90.3 µm and WMIR = 6 µm respectively [10].

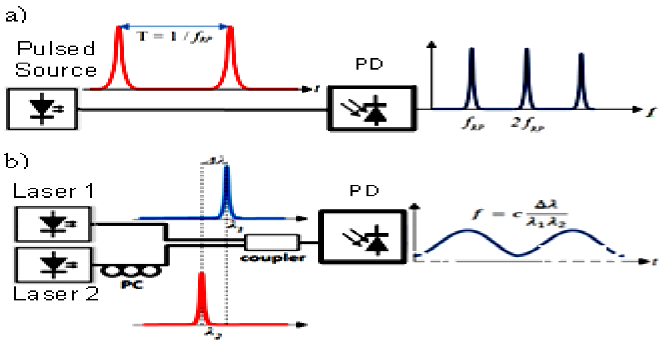

Fig. 1. (a) Pulsed source method. (b) Optical heterodyning method.

By taking into account the two main approaches, we have developed two different photonic integrated structures. The first device is an on-chip colliding pulse mode-locked laser diode. The structure of the OCCP-MLLD is depicted in Fig. 2(a). On the active area, based on shallow etched multi-quantum-well active layer, the waveguide includes semiconductor optical amplifiers (SOAs) for optical gain and the saturable absorber (SA) in order to achieve the mode locking structure. The SA is located at the center of the resonator cavity by defining the structure symmetrically from each side of the SA. On each side of the SA (length LSA = 20 um), we locate an SOA with the length LSOA = 390 um. The SOAs are followed by an active-passive transition and a passive waveguide. The SOAs are connected to the MIRs by passive waveguides. Thus, passive waveguides allow 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. The total length of the cavity is Lcav = 1234 um. On each side, a 2x0 MIR reflector defines the resonator and provides the optical output. A microscope photograph of the OCCP-MLLD sample is sketched in Fig. 2(b).

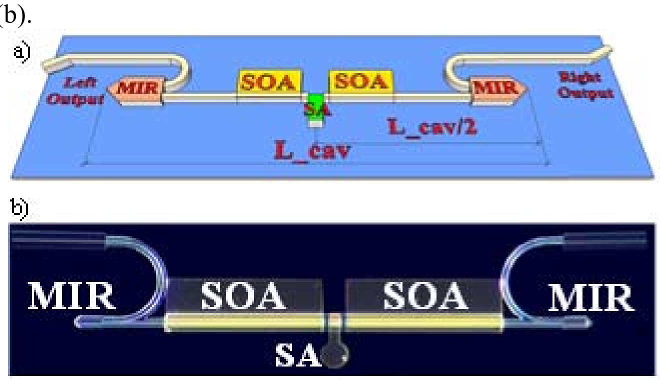

Fig. 2. OCCP-MLLD: (a) Structure. (b) Microscope photograph.

The second device is a dual wavelength source (OCCP-AWG) achieved by the on-chip integration of the OCCP-MLLD based on novel MIRs with an AWG optical filter. For the implementation of the OCCP-AWG, the output of the OCCP-MLLD is directly connected to the one input - two outputs AWG optical filter. Then, the AWG catch all the comb and select two modes according to the AWG transfer function from the optical frequency comb generated by the OCCP-MLLD. Thus, the selected two modes are combined in a multimode interference (MMI) coupler in order to approach the dual wavelength source. The structure of the OCCP-AWG is shown in Fig. 3(a). The key issue has been to design the pulse repetition rate at a sub-harmonic of the AWG channel spacing. In the dual wavelength source the channel spacing of the AWG is 90 GHz and the colliding pulse mode locked repetition rate is 30 GHz. With the colliding pulse repetition rate at 30GHz we can add an AWG filter with a channel spacing setting at a harmonic multiples of this frequency within the millimeter and terahertz range like 60 GHz, 90 GHz, 120 GHz, 150 GHz, 180GHz, 210 GHz, etc. As a result, we are able to design a dual wavelength source with a desired spacing within the millimeter and terahertz frequency range where the rule of thumb is that the colliding pulse repetition rate must be a sub-harmonic of the AWG channel spacing in order to select harmonic multiples of the comb provided by the OCCP-MLLD. Fig. 3(b) depicts the microscope photograph of the OCCP-AWG.

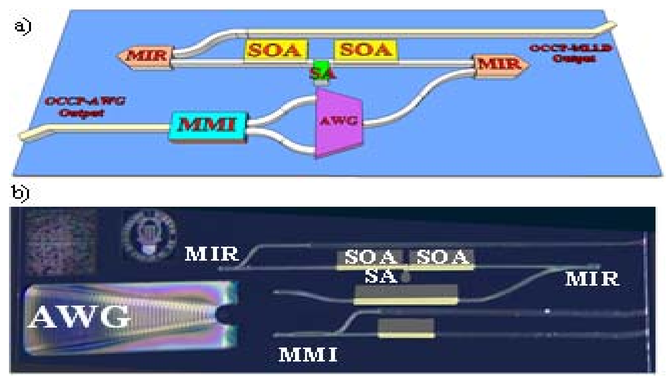

Fig. 3. OCCP-AWG: (a) Structure. (b) Microscope photograph.

III. Measurements and Characterization

The characterization was carried out by soldering these devices onto a copper mount and by controlling the temperature of the devices at 16 ºC using a thermo electric cooler (TEC). An 8-channel current controller ThorLabs ILX PRO-8000 was used in order to bias all the required SOAs and the SA was reverse biased with an Agilent E3631A voltage source. The light output from the chip was coupled to a fiber using a lensed fiber with AR tip coating. The optical characterization includes a Newport 842-PE power meter (PM) in order to measure the optical power and a Yokogawa AQ6370B optical spectrum analyzer (OSA), to observe the optical spectrum. The electrical characterization was performed by the Anritsu MS2668C electrical spectrum analyzer (ESA, frequency range 9 KHz – 40 GHz). Depending on the frequency range, we have external multiplication heads which down-convert the signal frequency in order to execute the electrical characterization in the ESA. For the OCCP-MLLD we used the external multiplication head from Anritsu, MA2744A (50 GHz - 75 GHz) while for the OCCP-AWG we employed the external multiplication head from Rohde-Schwarz, FS-Z110 (75 GHz - 110 GHz).

By performing the characterization of the OCCP-MLLD, we are able to sketch the optical spectrum in Fig. 4(a).To describe 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 central emission wavelength is 1562 nm, and the full-width half-maximum (FWHM) is Δv = 2.771 nm (345.8 GHz). The inset in Fig. 4(a) shows a detail of the optical mode spectrum, SMSR between the fundamental mode spacing (34.88 GHz) to the colliding mode spacing (69.76 GHz) is 24 dBm. Besides, we present in Fig. 4(b) the electrical mode beating spectrum of the OCCP-MLLD, when the device is biased in a colliding regime using the same conditions (I_{SOA} = 80 mA, V_{SA} = -1.7 V, resolution bandwidth RBW = 1MHz, video bandwidth VBW = 1 MHz). The electrical carrier tone at 69.76 GHz is depicted in the ESA due to the Anritsu MA2744A allows to display the measurement in the 50 GHz - 75 GHz range.

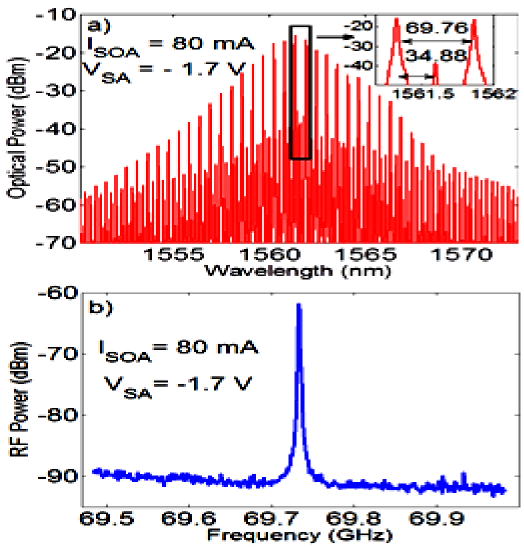

Fig. 4. OCCP-MLLD Spectrum: (a) Optical. (b) Electrical.

In the same way, the OCCP-AWG was characterized at the colliding pulse mode locked condition (I_{SOA} = 54 mA, V_{SA} = -1.7 V). The OCCP-MLLD provides a dual wavelength source which allows producing the heterodyning at 90 GHz. The optical spectrum of the OCCP-AWG is depicted in Fig. 5(a). Also, the electrical spectrum of the OCCP-AWG was characterized and sketched in Fig. 5(b). The heterodyning at 90 GHz is depicted in the ESA (RBW = 1MHz, VBW = 1 MHz) due to the down conversion provided by the Rohde-Schwarz FS-Z110 which allows to depict the electrical frequency at fo = 798 MHz by working with the 10^{th} harmonic.

IV. CONCLUSIONS

In summary, we report two different structures for the continuous millimeter and sub-terahertz wave signal generation. One approach is the pulsed source method, using the OCCP-MLLD based on MIR reflectors which allows reaching a carrier frequency at 70 GHz. The second approach is the OCCP-AWG, achieved by the on-chip integration of the OCCP-MLLD with an AWG optical filter, which allows achieving an electrical carrier frequency at 90 GHz.

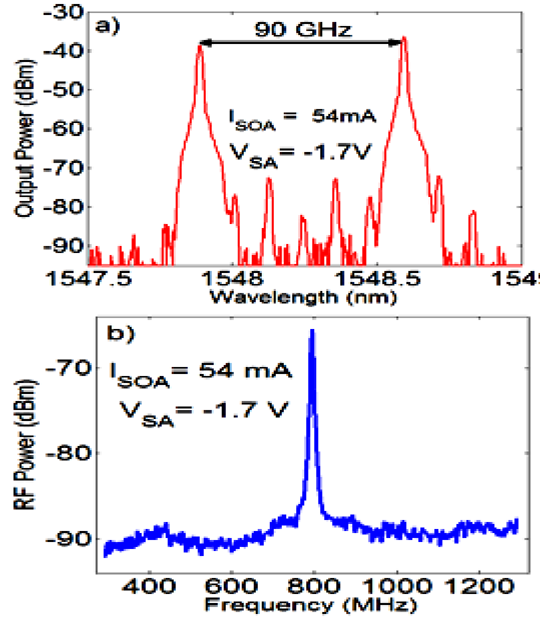

Fig. 5. OCCP-AWG Spectrum: (a) Optical. (b) Electrical.

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REFERENCES

[1] T. Kleine and T. Nagatsuma, T., "A review on terahertz communications research," *J. Infrared Millim. Terahertz Waves,* vol. 32, n°. 2, pp. 143–171, 2011.
[2] S. Koenig, D. Lopez, J. Antes, F. Boes, R. Henneberger, A. Leuther, A. Tessmann, R. Schmogrow, D. Hillerkuss, R. Palmer, T. Zwick , C. Koos, W. Freude , O. Ambacher, J. Leuthold, and I. Kallfass, "Wireless sub-THz communication system with high data rate," *Nature Photonics*, vol. 7, n°. 12, pp. 977-981, 2013.
[3] A. Stohr, "Photonic millimeter-wave generation and its applications in high data rate wireless access," *IEEE Top. Meeting on Microwave Photonics (MWP)*, 5-9 Oct. 2010.
[4] H .J. Song, T. Nagatsuma, "Present and Future of Terahertz Communications," *IEEE Transactions on Terahertz Science and Technology*, vol.1, n°.1, pp.256-263, Sept. 2011.
[5] M. Smit X. Leijtens, E. Bente, J. Van der Tol, H. Ambrosius, D. Robbins, M. Wale, N. Grote, M. Schell "Generic foundry model for InP-based photonics," *Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2012)*, paper OM3E.3.
[6] T. Nagatsuma, N. Kukutsu, and Y. Kado, "Photonic Generation of Millimeter and Terahertz Waves and Its Applications," *Applied Electromagnetics and Communications,* 2007. pp. 1-4 (2007)
[7] A. Stohr, S. Babiel, P.J.. Cannard, B. Charbonnier, F. Van-Dijk, S. Fedderwitz, D. Moodie, L. Pavlovic, L. Ponnampalam, C.C. Renaud, D. Rogers, V. Rymanov, A. Seeds, A.G. Steffan, A. Umbach, M. Weiss, "Millimeter-wave photonic components for broadband wireless systems," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, n°. 11 , pp.3071-3082, Nov. 2010.
[8] A. Hirata, M. Harada, T. Nagatsuma, "120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals," *Journal of Lightwave Technology*, vol. 21, n°. 10, pp.2145-2153, Oct. 2003.
[9] The pure play InP Photonics foundry, SMART Photonics, http://www.smartphotonics.nl/.
[10] E. Kleijn, M.K. Smit, X.J.M. Leijtens, "Multimode Interference Reflectors: A New Class of Components for Photonic Integrated Circuits," J. Light. Technol., 31, 3055 (2013).