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# Fully Monolithic Photonic Integrated Circuits for Microwave and Millimeter Wave Signal Generation

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*(Invited Paper)*

**Abstract**— We present two different photonic integrated circuits aimed to generate electrical signals within the microwave and millimeter wave range with two different techniques. The first approach uses the heterodyne technique, implementing a monolithic dual wavelength source by integrating on a single chip two distributed feedback (DFB) lasers together with the high speed photodiode. The second approach, using mode locked lasers, describes a novel device structure based on multimode interference reflectors (MIR).

## 1. INTRODUCTION

Recent technology roadmaps point to the need of increasing the data rates used in wireless communication systems into the multi-gigabit-per-second to cope with the future needs based in current trends of the demand [1]. 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 [2]. 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 links operating above 100 GHz employ photonic generation of the carrier frequency. There are many different photonic techniques available to generate continuous-wave (CW) frequencies, such as optical heterodyning using two frequency-tunable laser diodes, optical heterodyning using two modes filtered from a multi-wavelength source, combining a CW laser with external modulator and using mode-locked lasers [3].

On several of these approaches, fiber optic components were needed in the photonic system to generate the signal. It has been demonstrated that slight integration efforts lead to significant improvement in the generated millimeter wave signal quality, highlighting the importance of monolithic integration [4]. Currently, InP generic foundry models offer active-passive integration technology to fabricate Photonic Integrated Circuits (PIC) on Multi-Project Wafer (MPW) runs. Complex functionalities can be integrated on a single chip combining a small number of standardized basic building blocks (BB) with high performance [5]. In addition, because generic integration technologies can serve a large market, this allows approaching costs provided by economy of scale. In this work, we demonstrate recent advances in the development of PICs for microwave and millimeter wave signal generation, ranging from the monolithic integration of dual distributed feedback (dual-DFB) lasers to fully monolithic Mode locked laser diodes (MLLD).

On the first approach, described in Section 2, we show a fully monolithic millimeter-wave wireless transmitter, including two DFB lasers and optical combiners for the dual wavelength generation, electro-optic modulators (EOM) for data modulation, and, crucially, integrated high-speed photodiodes (PD) to generate the millimeter electrical signal. Semiconductor optical amplifiers (SOA) are also included to compensate the optical losses. This approach, which has the great advantage of continuous tuning of the wavelength spacing, requires a dedicated fabrication process flow to develop all these components in the same chip.

Finally, Section 3 reports a novel monolithic mode-locked approach, showing a novel cavity structure using multimode interference mirrors (MIR) that is fully integrated in the PIC, without need of cleaved facets. This is a step forward since in a MLLD, the length of the resonator defines the repetition rate. With this approach we have a lithographic control of the cavity length. Also,

we address the drawback of using cleaved facets that prevents its integration with other optical components into a PIC.

## 2. PHOTONIC INTEGRATED HETERODYNE SOURCES

Dual wavelength photonic integrated circuits have commonly been developed through monolithic integration of at least two single wavelength semiconductor lasers and combining the two wavelengths on-chip. Several approaches have been already demonstrated, using as single wavelength semiconductor laser either a Distributed Bragg Reflector (DBR) [6] or a Distributed Feedback Lasers (DFB) [7]. We have recently produced a significant advance, developing a photonic integrated circuits that includes two DFB lasers, both having a phase shift written in the middle of the Bragg grating to guarantee single mode operation, together with a  $2 \times 2$  multimode interference (MMI) coupler to combine the two wavelengths, bent SOAs to boost the optical power within the waveguides, and monolithically integrated Uni-Traveling Carrier photodiodes (UTC-PD). Between each MMI output and the UTC-PD, the light passes through another bent SOA (to boost the optical signal after passing through the combiner), an electro-optical modulator (to introduce the data modulation on-chip) and a straight SOA (to boost the signal entering the photodiode). The chip also provides an optical output combining the two wavelengths through a  $2 \times 1$  MMI coupler. This combiner has been included in order to allow phase noise reduction through optical injection locking. The whole device is 4.4 mm long and 0.7 mm wide.

One of the main technological achievements of this approach has been the development of a fabrication process flow that allows the growth of the different components, in particular the high-speed photodiodes, in the single PIC. The layers were grown on a semi-insulating InP wafer in order to reduce the parasitic capacitance and get a sufficiently large detection bandwidth of the photodiodes. Active/passive integration is achieved using a butt-joint process. The active layers consist of 6 InGaAsP quantum wells. DFB lasers, SOAs and modulation sections contain the same quantum well stack. The Bragg grating is formed in an InGaAsP layer placed above the quantum wells and defined by e-beam lithography. The UTC layers are similar to the ones used in [8], are grown above the passive waveguide, to implement two  $3 \times 15 \mu\text{m}$  UTC-PD. The fabrication required 3 epitaxial growth steps. After wafer thinning and back metal deposition a first set of measurements were performed directly on the wafer. After these first measurements, chips were cleaved and mounted on AlN submounts.

Using the left-hand side optical output of the device shown in Fig. 1, we have been able to measure simultaneously the spectrum of the optical signal generated by the chip and the generated high frequency electrical signal from the monolithically integrated UTC photodiodes when the DFB lasers were electrically tuned and some of the SOAs biased. For the measurements showing the tuning range of the two wavelengths, one of the DFB lasers was biased with a current varying from 50 mA to 86 mA while the other was biased with a current varying within a 50 to 198 mA range. Within these bias ranges, the UTC photocurrent varied between 1.12 and 6.27 mA. During operation, the photodiode is reversed biased at 2.5 V. Dark current of  $< 10 \mu\text{A}$  was measured at this bias point. The measured optical spectra are presented in Fig. 2, where for the shown sample a continuous tuning of the optical frequency difference between the two DFB tones from 5 to 110 GHz is observed. The wavelength tuning is thermal through changes in the DFB bias current. Also, as the two lasers are close to each other, we observe thermal cross-talk between the two lasers.

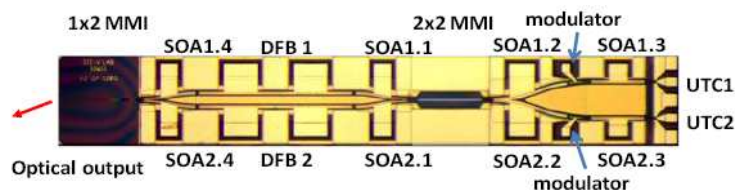


Figure 1: Microscope view of the dual DFB dual wavelength source.

Figure 3 shows the electrical spectra corresponding to the different bias conditions shown in Fig. 2, measured using a Rohde & Schwarz FSU67 electrical spectrum analyzer, with a FS-Z110 external mixer for measurements above 65 GHz. As the electrical spectrum shows, we observe the heterodyne signal without noticeable effects of the additional optical tones, although may have a negative effect generating a photocurrent and potentially limiting the maximum generated electrical power. In order to measure the maximum electrical power, we biased the two DFB lasers at 95 mA,

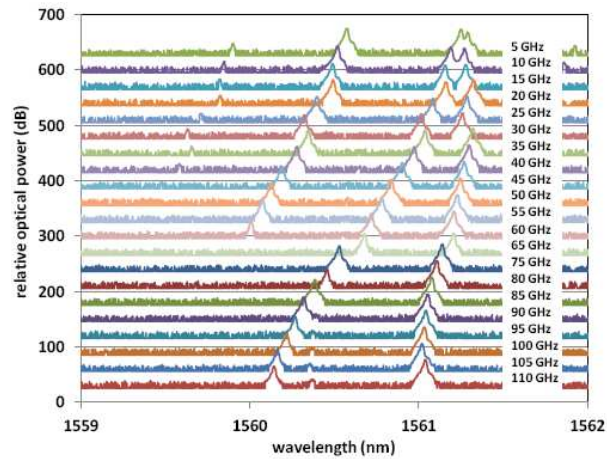


Figure 2: Optical spectrum at the optical output varying the current injected on the two DFB.

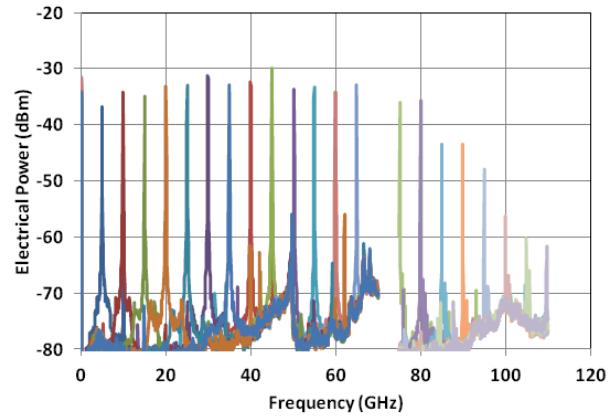


Figure 3: Electrical spectrum at the output pads of the monolithic UTC photodiode.

generating a wavelength spacing of 95.7 GHz. We measured  $-12$  dBm detected power on an Agilent E4418B EPM series power meter with a W8486A power sensor a maximum when the photodiode was reversed biased to  $-2.5$  V with 8.76 mA generated photocurrent. The losses due to RF probe and signal free space propagation path ( $< 3$  cm) between antenna on the probe and power meter are not corrected.

### 3. PHOTONIC INTEGRATED MODE LOCKED SOURCES

Several wireless communication links that have been reported, operating above 100 GHz, employed pulsed sources to generate the carrier frequency. The pulsed system output  $\sim 7$  dB more power at the same  $P_{\text{opt}}$ , than heterodyne ones, suggesting that the conversion process depends more on the peak than the mean optical power. The drawback is that most mode-locked laser diodes (MLLD) usually require cleaved facets to create the cavity. We present here an alternative to mode locked ring lasers, in which the mirrors are defined by Multimode Interference Reflectors (MIR) [10], creating a novel mode locking structure shown in Fig. 4. The rectangular metal contacts upwards are the SOA sections. The downward contact is the saturable absorber section, and the extremes are  $2 \times 0$  MIR reflectors, with 50% reflectance, providing the other 50% at the output on both ends. The device was fabricated in a Multi-Project Wafer (MPW) run for InP-based Photonic Integrated Circuits (PICs). The total length of the cavity is  $2210 \mu\text{m}$ , which defines a frequency spacing of 18.67 GHz. The use of MIR reflectors gives full flexibility on the location of the device within the Photonic Integrated Circuit chip, except for the extremes, which are now of finite length, and in a passive epilayer. Thus we have located the SA along the active epilayer region, at the midpoint ( $L/2$ ) of the cavity, to achieve a repetition rate at the second harmonic, 37.34 GHz by colliding pulse mode locking. Other locations for the SA are shown in the microscope photograph of the device in Fig. 4.

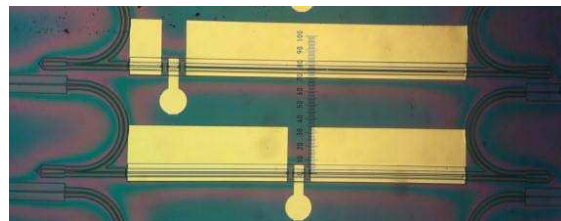


Figure 4: Microscope view of the monolithic mode-locked laser diode (mMLLD).

The device was characterized on a copper chuck stabilized in temperature to  $17^\circ\text{C}$ . The light outputs the chip through angled facets which are AR-coated. The optical spectrum, shown in Fig. 5, was observed collecting the light with an anti-reflection lensed fiber followed by a Yokogawa AQ6370B optical spectrum analyzer. The mode locking of the laser was studied observing the RF spectra, recorded on an Anritsu MS2668C Electrical Spectrum Analyzer and a XPDV2120R U2T photodiode with 50 GHz bandwidth. The mode beating spectrum with  $I_{\text{SOA}} = 90$  mA and  $V_{\text{SA}} = -2.5$  V is shown in Fig. 6(a), showing the fundamental frequency peak at 46.49 dB over the

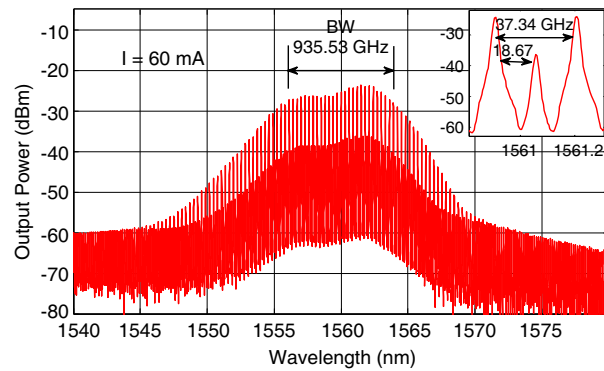


Figure 5: Optical spectrum at the optical output of the mMLLD.

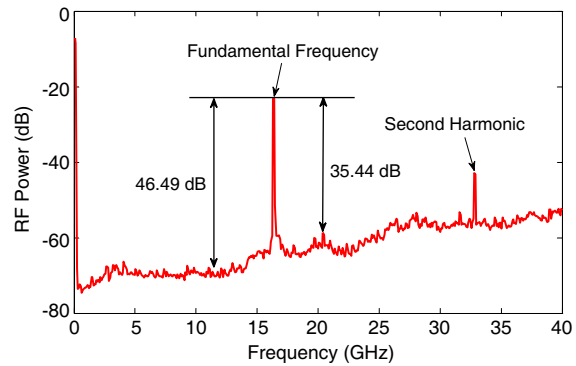


Figure 6: Electrical spectrum of the mMLLD.

noise floor at  $f_{\text{rep}} \sim 16.7$  GHz. The FWHM linewidth of the beating RF spectrum, when fitted to a Lorentzian lineshape is 91.90 kHz.

#### 4. CONCLUSIONS

We have presented two different photonic integrated circuit approaches to generate carrier waves within the millimeter-wave frequency range. The approach using two monolithically integrated DFB lasers has the main advantage of the frequency tuning range, covering from 5 GHz to 110 GHz in a single device. We also report for the first time a new class of mode locked sources based on monolithic MIR reflectors, which can be integrated within a chip.

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