Microwave Photonics: Opportunities for Photonic Integration

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Abstract. *This paper reviews the prospects and technologies for integration in microwave photonic systems. An advanced application - photonic THz - generation is used to illustrate the potential value of photonic integration. Integration technologies for this system based on quantum well intermixing, monolithic integration on indium phosphide and hybrid integration using silicon motherboard technology are described. Finally, some pointers to future applications of integration are given.*

Introduction

Microwave photonics can be defined as the study of opto-electronic devices and systems operating at microwave frequencies and their use to process microwave signals [1]. The ability to transport microwave bandwidth signals over long (km) distances with little penalty has proved of particular commercial interest, with sales of systems for distributing cellular radio and other wireless signals amounting to some $250 m, annually.

Key components required for microwave photonic applications include optical sources that can be modulated at high frequency, high speed photodetectors, optically controlled microwave devices, and suitable transmission media. Thus current microwave photonic systems are largely based on discrete photonic components.

Directly modulated semiconductor lasers are limited to modulation frequencies of about 40 GHz [2], and external modulators are limited to modulation frequencies of about 100 GHz [3], while photodetectors operating at THz modulation frequencies have been realised [4, 5]. The desire to access modulation frequencies higher than those available with directly modulated lasers or external modulators has led to more complex source solutions [6], and here photonic integration could offer significant advantages in terms of performance, environmental stability, compactness and cost.

In this paper integrated solutions to achieving high modulation frequency operation are described, based on a particular application: photonic generation of THz signals. After describing the system approach, the potential applications of quantum well intermixing, monolithic integration and hybrid integration to the realisation of the THz generator system are described. The paper concludes with comments on likely future applications of integration technology for microwave photonics.

The THz generator

THz signals (frequencies in the range 100 GHz to 10 THz), have attracted considerable attention in the past few years, due to their broad range of applications, from ultra-high bit-rate wireless communications to security, imaging, and radio-astronomy [7]. At present a major limitation in wider exploitation of devices working at these frequencies is their lack of portability and frequency agility. Femtosecond-based systems are bulky and have large primary-power requirements [8] while Quantum Cascade Lasers (QCL) [9] have limited tunability. The optical heterodyne technique, also known as photo-mixing [4], offers wide tunability but limited frequency stability. A solution to the frequency stability problem is to derive the optical signals from an optical frequency comb, where the comb-line spacing is determined by a microwave reference signal. A schematic of such a system is shown in Fig. 1. The main elements required are an Optical Frequency Comb Generator (OFCG), two Optical Phase Lock Loop (OPLL) systems [10-13], which serve as tuneable active optical filters to select the required comb lines, an ultra-fast photodetector and an antenna. The OPLL is the chosen technology as it offers better tracking and larger locking bandwidth than Optical Injection Locking (OIL) [14]. The OFCG generates a comb of optical frequencies separated by the supplied microwave reference frequency and the OPLLs select two comb lines separated by the required THz output frequency. The two optical signals produced from the OPLLs are then combined on the same optical path to feed the fast photodetector [4, 5]. The generated THz signal is then coupled to an output transmission line or antenna [14].

In order to realise a portable system, integration of the various components in the THz generator is a fundamental requirement, but it is also a serious challenge, due to the need to define several different functionalities on a common platform.

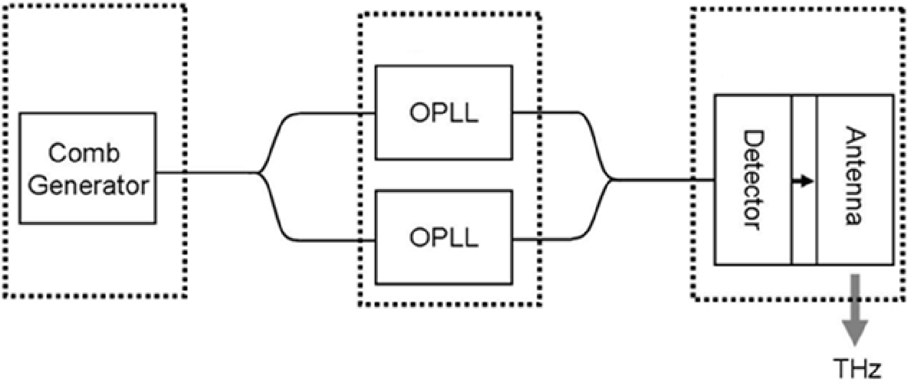

Figure 1: Schematic of the photonic THz generator.

Optical frequency comb generator - an intermixing approach

The reference source in the THz generator is an OFCG. Fibre-based approaches have been demonstrated but require careful adjustment and have limited environmental stability [15-16]. A more compact frequency comb can be generated using deep angle modulation [17], however for such systems the power from each line is limited (from 10 mW/line at the seed laser peak down to 1 nW/line at 3 THz from the peak). Mode-locked semiconductor lasers can provide compact comb sources [18] but the strong intensity modulation can give rise to saturation problems in the OPLL photodiode. This issue can be avoided through the use of the Frequency Modulated (FM) laser technique. In the FM laser, the mechanism that induces coupling between the different longitudinal modes is the modulation of the cavity phase. When the modulation frequency is set close to the laser axial frequency, the generated optical spectrum consists of a comb of lines spaced by the modulation frequency. The FM laser diode is a typical example of a structure where integration is needed in order to define different functionalities within a monolithic device. Given that the standard material platform used to fabricate high performance semiconductor lasers is based on Multi Quantum Well (MQW) epitaxial structures, which are typically defined during a first epitaxial growth, it is then necessary to define different core regions for the gain and for the modulation sections. Several approaches are possible, such as butt-joint regrowth [19], the twin waveguide structure [20], or Quantum Well Intermixing (QWI) [21]. Butt-joint structures require etching and regrowth steps to define the wanted material structure adjacent to the gain section. Particular care has to be taken to avoid reflections at the interfaces and material contamination. However, when the technique is well established, it allows fabrication of very high performance devices. The twin waveguide technology consists of defining two (or more) different core regions, for instance gain and phase tuning, on top of each other separated by a transparent optical coupling medium. Its main advantage is reduced complexity in post-growth fabrication; however limitations in the range of coupling that can be achieved between regions restrict device performance. QWI affects the material by rearranging the quantum well structure in the core region. The process is used to blue-shift the core band-gap in order to obtain the desired trade-off between absorption losses and efficient tuning of the refractive index. The main advantage of this technique is that it does not require regrowth, thus simplifying fabrication.

A monolithic FM laser comb generator has been fabricated as a Ridge Waveguide (RWG) structure [22]; the device design, which comprises a gain section, a phase adjustment section, and a frequency modulation section, is shown in Fig. 2. The fabrication was carried out entirely post-growth, following a single Metal–Organic Vapour Phase Epitaxy (MOVPE) epitaxial growth of the InGaAsP-InP material on a Semi-Insulating (SI) InP substrate.

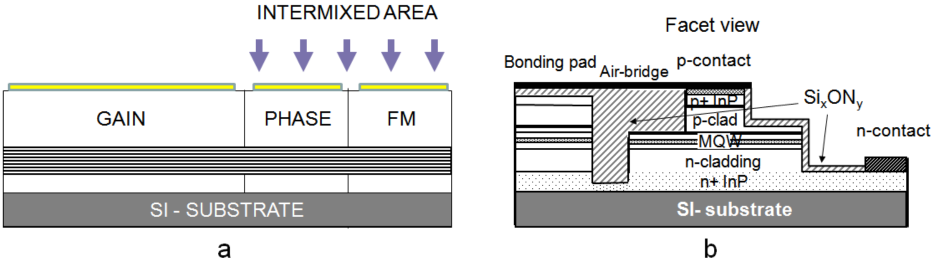

Figure 2: (a) Schematic of the monolithic FM laser (lateral view); (b) Transversal section of the same laser, showing the layer structure.

In order to guarantee optimal phase adjustment and tuning, the energy bandgap of the phase and modulation sections of the laser were intermixed by shallow ion implantation. The process consisted of exposing the phase and modulation sections of the devices to a beam of P ions impinging on the sample with energy of 100 keV. After implantation, a Rapid Thermal Annealing (RTA) process was carried out, at 650 °C for 90 seconds. The result was a 35-nm blue-shift of the bandgap of the implanted regions, as shown in

Fig. 3. In order to ensure good electrical isolation between the different sections, isolation trenches were defined by plasma etching.
The other critical technological feature of these lasers, which was necessary to provide high modulation frequency performance, is the oxide-bridged p-contact. This is an Au bridge that connects the laser ridge to the device bond-pad, and that is supported by a silicon oxynitride layer (see Fig. 2b). A picture of the final device is shown in Fig. 4.
Testing of the fabricated FM lasers shows a comb spectrum, with lines spaced exactly by the 24.4 GHz modulation frequency, as shown in Fig. 5. The intensity modulation is less than 20% and the total output power is 2 mW. Although the comb spectrum is not continuous across the full span, due to Fabry-Perot cavity effects resulting from the isolation trench etches, the potential comb spectrum width appears to be up to 2 THz (15 nm).

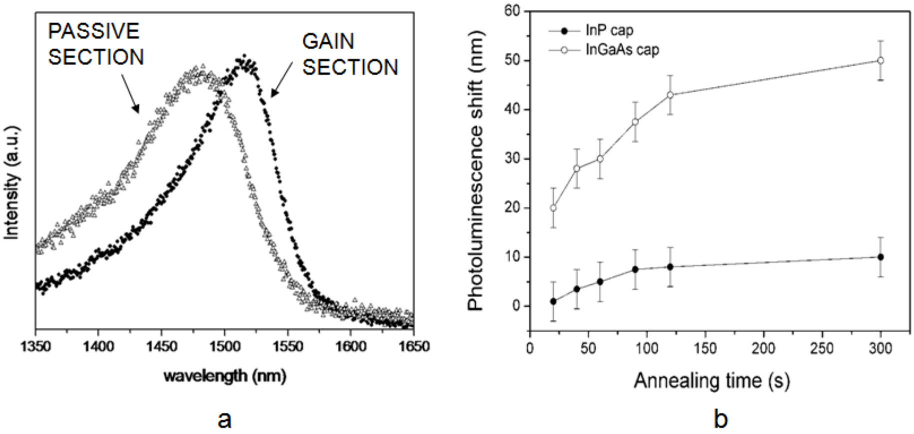

Figure 3: (a) Photoluminescence (PL) spectrum of passive and active sections after QWI; (b) PL shift versus annealing time (at 650 °C).

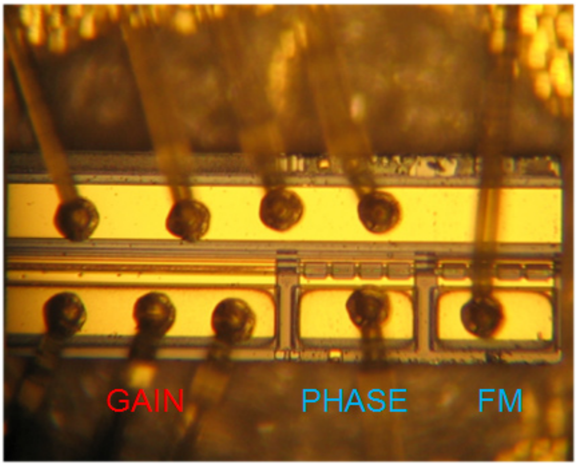

Figure 4: Micrograph of the fabricated OFCG.

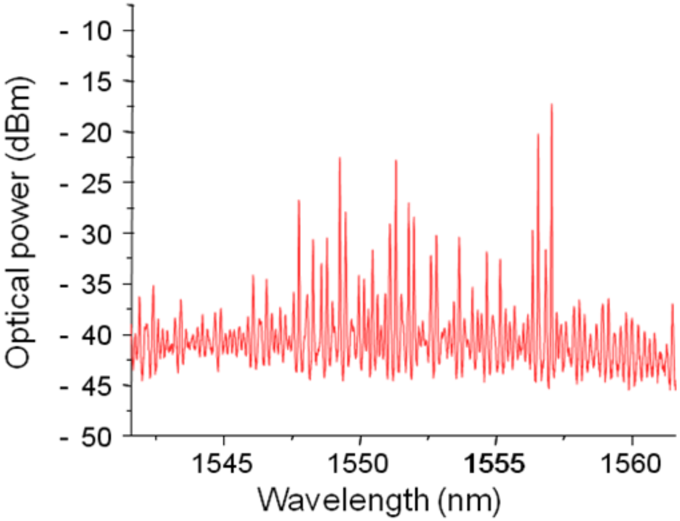

Figure 5: Optical spectrum of the InGaAsP-InP QCSE OFCG.

Distributed Bragg Reflector (DBR) laser - a source for both monolithic and hybrid integration

In an OPLL, Fig. 6, a tuneable laser is locked to the required comb-line. The tuning range of the laser should be sufficient to access at least half of the comb spectrum, requiring a tuning range of around 8 nm for operation with the comb generator of the previous section.

DBR devices for both monolithic and hybrid integration have been designed which share a common buried heterostructure four-section DBR laser design. The gain is provided by a strain compensated 8 well MQW active layer, with an 80 nm thick quaternary alloy composed of 1.2 µm wavelength material on the n-side of the active layer. In the phase and grating sections the active layer was removed and a 225 nm thick layer of bulk 1.4 µm wavelength quaternary material was butt coupled to the active layer. The thickness and composition were chosen to provide a good optical mode match to the active material. The grating was defined by etching through another 40 nm thick p-doped 1.4 µm wavelength quaternary, 300 nm above the top of the main passive waveguide. The grating layer thickness was chosen to give a kappa of ~ 39 cm^{-1}.

The rear grating, phase, active and front grating sections are 450 µm, 100 µm, 400 µm and 150 µm long respectively. The electrical isolation between the sections was provided by etching out the ternary contact from a 20 µm long region between each of the contact sections.

The devices designed for hybrid integration also included a curved passive waveguide section in front of the short front grating followed by a twin guide mode expander [23] with a 500 µm long taper section and 100 µm long passive waveguide section at the output facet. Two design variants were included, in the first the mode expander was passive and was composed of the same bulk 1.4 µm quaternary material as the phase and grating sections, in the second design the mode expander consisted of the strain compensated MQW active structure and was used to provide a Semiconductor Optical Amplifier (SOA) power booster/shutter.

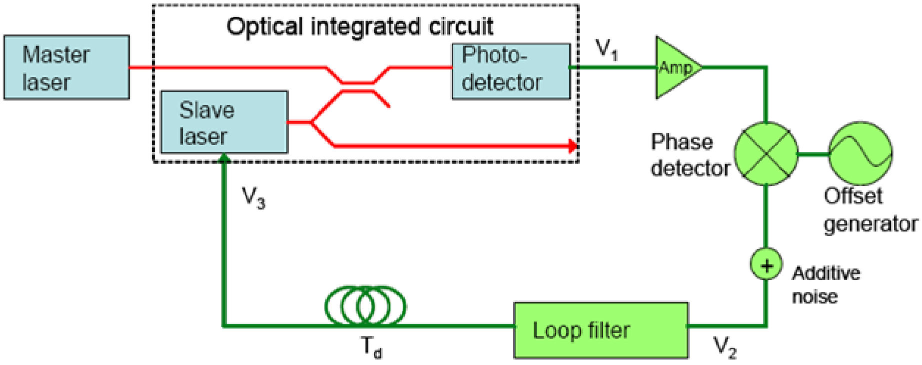

Figure 6: Schematic of the OPLL part of the THz generator.

Optical phase lock loop - a monolithic approach

The configuration of a single OPLL filter for use in the THz generator is shown in Fig. 6: light emitted from the master laser and the slave laser is coupled onto a photodetector, which generates an electrical error signal of frequency equal to the frequency difference between the two sources. The PLL circuit performs a comparison between the phases of the two signals and adjusts the slave laser conditions in order to lock the slave laser to the master source. If the slave laser has a relatively wide linewidth (> MHz), a short loop propagation delay (< ns) is required in order to achieve adequate phase noise reduction [24]. It follows that the choice of developing an integrated THz system, besides providing a compact and portable THz source, offers the advantage of a short delay optical and electronic circuit design, which allows use of standard single-mode laser diodes with linewidths around 1 MHz. This demonstrates the clear advantage in reducing the loop delay, which is possible by integration of the OPLL optical circuit. A monolithic integration scheme offers the shortest optical paths and is therefore attractive.

The layout of the optical part of the OPLL is shown in Fig. 7. The material system chosen to develop the device is phosphorus quaternary, for compatibility with the telecommunications components-base, working at 1.55 μm wavelength.

Following growth, by MOVPE, of the MQW InGaAsP-InP wafer, the various building blocks of the single optical OPLL are defined on the same chip. These elements, which are depicted in Fig. 7, are a tuneable laser, passive waveguides, and a photodiode. The slave laser uses the four-section DBR laser design of the previous section, and is optimised to provide a wide wavelength tuning range of approximately 8 nm. The integration approach chosen to define the phase, grating and passive sections is by MOVPE selective area regrowth technique. This choice is primarily driven by the need not to compromise the laser performance. The detector is designed based on a simpler ridge waveguide structure, whose absorbing region has the same active structure as the laser, to provide a maximum bandwidth of 10 GHz.

Particular attention has been given to the design of the active-passive interfaces, as it is critical to the performance of the integrated device that internal reflections are suppressed. All active-passive interfaces have therefore been angled at 20 degrees, and successive interfaces angled in opposite directions, an approach that has given good results in multisection tuneable lasers [25].

A major advantage that is expected from the monolithic approach will be given by further integration of two OPLL optical modules. In that case the two lasers will be integrated on the same chip, which will ensure thermal tracking between the two sources, reducing the drift correction requirements on the control loop.

Recently, buried heterostructure DBR lasers were fabricated, based on the design of the previous section. Preliminary results on assessment of their linewidths are shown in Fig. 8. These measurements demonstrate that with such a design it is possible to achieve a laser linewidth of around 1 MHz, narrow enough to guarantee excellent OPLL phase noise performance.

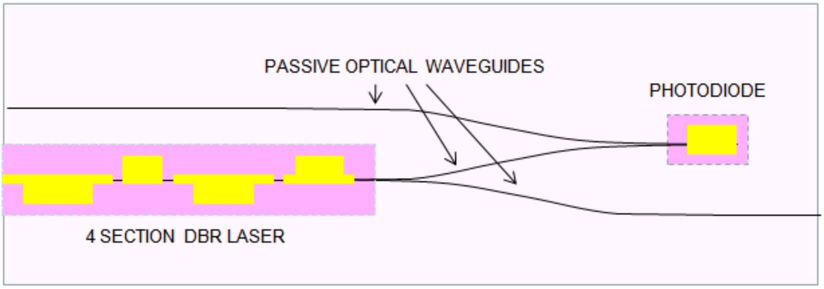

Figure 7: Monolithic design for the optical part of the integrated OPLL.

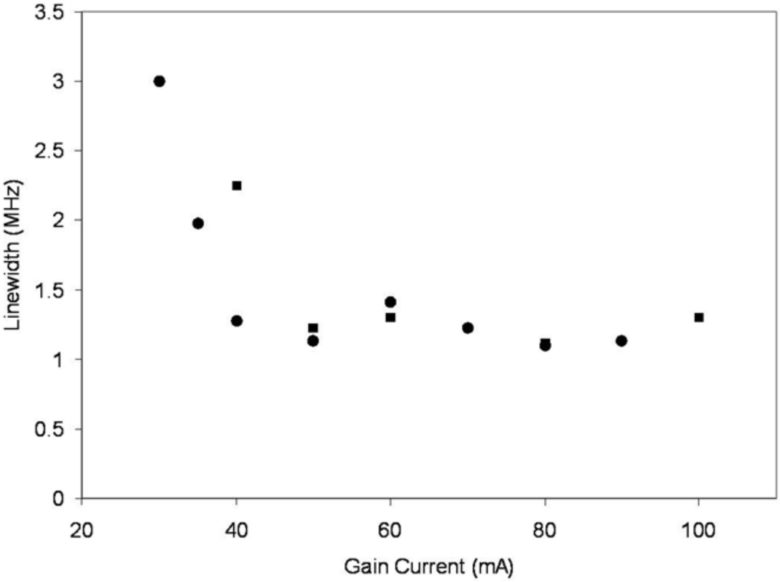

Figure 8: Linewidth measurements for two samples of buried heterostructure DBR laser.

THz generator system - a hybrid approach

In the hybrid integration work, the aim is to integrate the entire optical part of the THz generator onto a single motherboard. In this approach, each optical element is developed separately, on its optimal substrate, the various elements are then combined on a common silicon motherboard [26]. This motherboard is designed to include passive optical waveguides and combiners, defined on silica, and etched slots, where the active components will be placed. A third class of components, called daughterboards, is designed to define the electrical and physical interface between each active element and the motherboard. The complete device comprises, therefore: separate active components for each function (in this case comb generator, lasers and photodetectors); a separate daughterboard designed specifically for each of these components, using precision micromachining to give passive alignment to the passive optical waveguides; and a common motherboard which defines the functionality of the overall device. Clearly, a major advantage of this approach is that in this way the performance of each element can be optimised, without compromising on overall performance.

In the proposed hybrid design, the slave lasers of the two OPLLs are designed as one twin DBR laser unit, comprising a pair of closely-spaced tuneable lasers of the type described in the previous section. The photodiodes are designed to have bandwidth greater than half the comb line spacing, typically 15 GHz. As with the monolithic device, operation of the hybrid device is critically sensitive to back reflections, with a requirement that there should be no reflections back into the laser cavity above a threshold of -50 dB return loss [27]. Angled interfaces are therefore used in the hybrid design. However, since all the interfaces in the system occur at points where the mode size has been expanded to ease alignment tolerances, in this case an interface angle of 10 degrees is sufficient to give the required return loss. As with monolithic OPLLs the physical dimensions have to be minimised to control the delay in the phase error feedback loop; attention has therefore been paid in the design to placing the photodiodes as close as possible to the DBR laser output facet, with an absolute upper limit of 10 mm on this dimension.

Conclusions

In this paper we have reported recent advances in the area of integrated microwave photonics. To illustrate some of the technologies required, we have focused on a specific system, namely the photonic THz generator. Such a compact THz source would be highly appealing, both in terms of performance and portability. We have shown how it is possible to develop key elements of the THz synthesizer using a range of integration technologies chosen for their contrasting advantages.

Considering the prospects for integration technologies in microwave photonics more generally, the strong current interest in advanced modulation schemes for optical communications, including coherent receivers, requires complex phase stable sources and receivers operating at data rates requiring microwave photonic techniques. There is here a major opportunity for photonic integration to create a large functionality, low cost components base.

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