Photonic Integrated Circuits: from Techniques to Devices

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Abstract: The advantages and challenges of InP Photonic integrated circuits are summarized. Four common photonic integration techniques and five PIC devices for different applications are introduced.
OCIS codes: 250.5300, 140.5960,160.5293.

1. Introduction

Photonic integrated circuits (PICs) are the next logical step in the world of optics and can be used in fiber-optic communication, biomedical, and photonic computing. Normally the term PIC incudes three classifications, the first being the III-V PIC, the second the silicon PIC, and the third hybrid integration, i.e., III-V devices integrated on a silicon substrate. At present, silicon photonics is a solution for connections within data centers, and in the future for chip-to-chip interconnects and even intra-chip connections. The future for silicon PICs includes integration with the CMOS process. In this presentation, we will just focus on the III-V PIC, more specifically the InP PIC. An InP PIC is a device that integrate multiple components with different photonic functions, material compositions, bandgaps, doping concentration distributions, and refractive indexes on a single substrate [1]. Compared with the electronic integrated circuit (EIC) whose dominant material is silicon, PICs place many more challenges on the fabrication processes. Compared with discrete photonic devices, PICs have following advantages: 1) increased bandwidth; 2) expanded frequency (wavelength) division multiplexing; 3) low-loss component-to-component coupling; 4) increased multiple switching; 5) small size, weight, low power consumption; 6) batch fabrication economics; 7) improved reliability; 8) improved optical alignment, immunity to vibration. PICs are the key for realizing multifunctional, low-cost devices for optical communications and for other miniature and portable optical systems. PICs can precisely control the light in terms of power, wavelength, linewidth, phase, pulse repetition frequency and pulse width. The challenges for PICs are as follows: 1) accurate control of the different bandgap wavelengths required by different components on a single substrate; 2) efficient optical coupling between the various components; 3) low electrical and optical crosstalk between the various components; 4) independent optimization of each component; 5) high coupling efficiency between the chip and the fiber; 6) simplicity in fabrication; 7) high yield.

2. PIC techniques

For more than the last 30 years, researchers have proposed and implemented many photonic integration technologies, such as: 1) butt-joint growth (BJG); 2) bundle integrated guide (BIG); 3) double-stack active layer (DSAL); 4) quantum well intermixing (QWI); 5) selective area growth (SAG); 6) asymmetric twin waveguide (ATG). Among these PIC techniques, there are four common techniques: BJG, SAG, QWI, ATG. Using the BJG techniques it is possible to optimize each component independently, but its big challenges are how to control the etching and regrowth sufficiently precisely, how to avoid defect generation during regrowth and how to obtain a high quality butt-joint interface with low scattering loss. SAG technology is useful in fabricating active devices with different bandgap energies simultaneously, however it is not suitable for the integration of active and passive devices. The ATG technique needs multiple steps of material etching with accurate control, especially for etching active tapers, and there is an inevitable transmission loss from active to passive waveguides. ATG does not have the flexibility necessary for large-scale photonic integration due to its limited number of bandgaps. Compared with above three photonic integration techniques based on selective etching and re-growth, post-growth processing based on QWI offers a simple, flexible and low-cost alternative [2]. Table 1 summarizes the characteristics of these four different photonic integration process techniques.

3. PIC devices

Here five different PIC devices for different applications using the integration techniques in Section 2 are introduced:

3.1. Electroabsorption modulated semiconductor optical amplifier monolithically integrated with spot-size converters using SAG, QWI and ATG techniques (Fig. 1) [3]. Applications include encoding, optical switching and wavelength conversion.

3.2. EAM modulated DBR laser array using BJG, and SAG techniques (Fig. 2) [4]. Applications include TWDM-PONs.

3.3. Monolithically multi-color 40 GHz mode-locked laser arrays using QWI techniques (Fig.3) [5]. Applications include high speed optical sampling, photonic microwave systems and next generation optical communication systems.

3.4. Fully integrated optoelectronic synthesizer using QWI techniques for THz communications (Fig. 4) [6].

3.5. 1.55 μm DFB laser monolithically integrated with power amplifier array using QWI techniques (Fig. 5) [7]. Applications include Raman pumps for fiber communication systems, spectroscopy, remote sensing, free-space communications, eye-safe laser-based radar (LIDAR), and wavelength conversion in nonlinear materials.

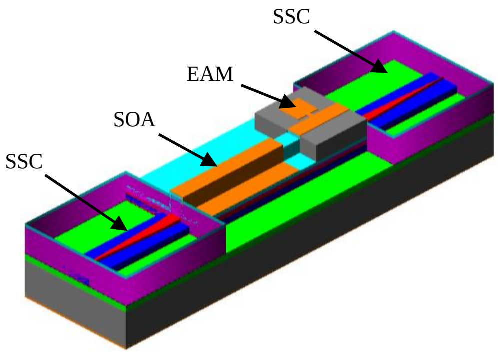

Fig. 1. Device of SSC-SOA-EAM-SSC

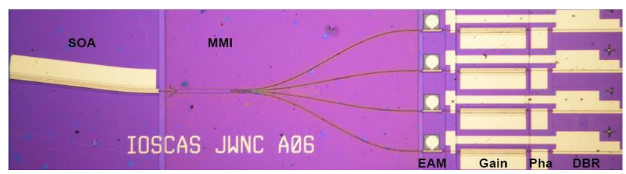

Fig. 2. EAM modulated DBR laser array

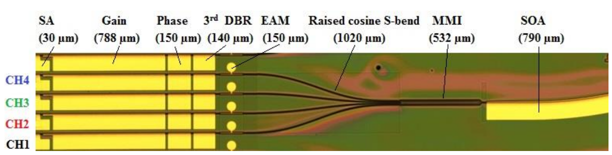

Fig. 3. Monolithic multi-color 40 GHz mode-locked laser array

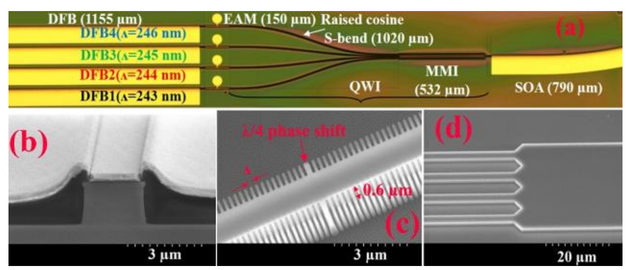

Fig. 4. Fully integrated optoelectronic synthesizer

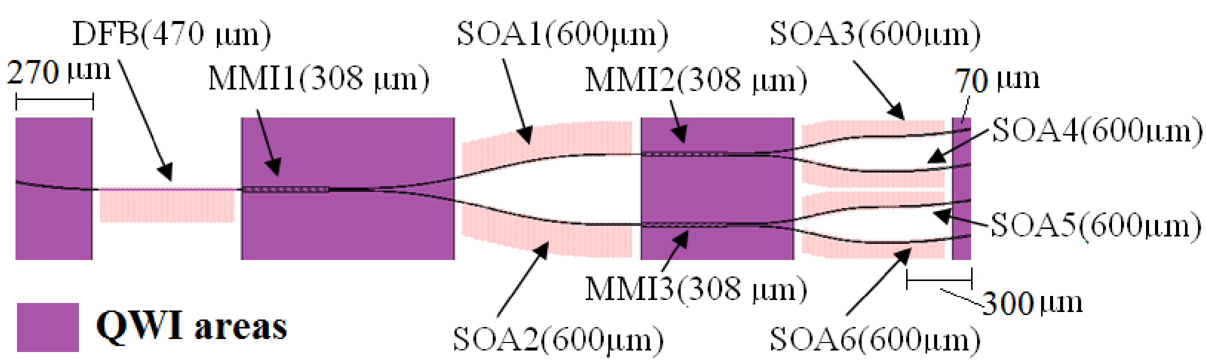

Fig. 5. 1.55 μm DFB laser monolithically integrated with power amplifier array.

Table 1. Comparison of different photonic integration techniques

PIC techniques / Process characteristics	BJG	SAG	QWI	ATG
Regrowth?	Y	N	N	N
Number of integrated band gap materials	Each regrowth adds a material	Multiple (Depends on the mask design)	Multiple (By controlling the concentration of point defects in different regions)	An etch step usually enables a kind of material to be accessed
Requires precise control of lithography and etching techniques?	Y	N	N	Y
Interface between different materials	Steep	Gradual transition 50~100 μm	2-3 μm	Gradual transition 100~200 μm
Allows full optimization of different materials?	Y	N	N	Y
Integration of bulk material is possible?	Y	N	N	Y
Enables precise control of the band gap wavelength?	Y	Y	N	Y
Other		Can achieve a gradual change in thickness		

3. References

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