Integrated Microwave Photonics

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We review the general aspects of this emerging field including the state of the art in material technologies and demonstrated functionalities, and some recently proposed novel approaches.

Introduction

Microwave Photonics (MWP) [1-3] a discipline that brings together the worlds of radiofrequency engineering and optoelectronics, has attracted great interest from both the research community and the commercial sector over the past 30 years. The added value that this area of research brings stems from the fact that, on the one hand, it enables the realization of key functionalities in microwave systems that either are complex or even not directly possible in the radiofrequency domain and, on the another hand, that it creates new opportunities for information and communication (ICT) systems and networks.

While initially the research activity in this field was focused towards defense applications, MWP has expanded to address a considerable number of civil applications[3-5], including cellular, wireless, and satellite communications, cable television, distributed antenna systems, optical signal processing and medical imaging systems using terahertz (THz) waves. Many of these novel application areas demand ever-increasing values for speed, bandwidth and dynamic range while, at the same time, require devices that are small, lightweight and low-power, exhibiting large tunability and strong immunity to electromagnetic interference.

For the last 30 years, MWP systems and links have relied almost exclusively on discrete optoelectronic devices, standard optical fibers and fiber-based components which have been employed to support several functionalities like RF signal generation, distribution, processing and analysis. These configurations are bulky, expensive and power consuming while lacking in flexibility. A second generation, termed as Integrated Microwave Photonics [6] (IMWP) which aims at the incorporation of MWP components/subsystems in photonic circuits, is crucial for the implementation of both low-cost and advanced analog optical front-ends and, thus, instrumental to achieve these targets. In this paper we review the general aspects of this emerging field including the state of the art in material technologies and demonstrated functionalities, and some recently proposed novel approaches.

State of the Art and Functionalities

A. Material Technologies

Due to the stringent requirements in handling analog signals, PIC technology for integrated MWP should show high performance, most of the time higher than the one expected from the digital applications. Moreover, in the present state, MWP is addressing lower volume markets, and therefore lower volume PIC productions. These are the aspects which force PIC technology players to take a different approach to integrated MWP.

Although IMWP is still in its infancy, several functionalities have been demonstrated so far in different material technologies. Table I gives a general overview per material technology of the building blocks available, that are required in a MWP system [7]. Active materials, i.e. those able to generate / amplify light, such as GaAs and InP (and combinations) excel in light generation, detection and modulation. Silicon materials may well be split in three subfamilies: Silica (fiber-like) waveguide technology, not shown in the table owing to the fact the density of integration is low (comparatively lower index contrast), despite it provides good passive devices; Silicon (Oxy)Nitride and Silicon-on-Insulator (SOI). While nitride based technology provides superb filtering and packaging solutions, SOI provides light detection, modulation and natural merge with electronics. Table II gives a technical overview per material technology. The first two rows, refractive index contrast and bend radius, are related to the circuit footprint. The third entry, attenuation coefficient, together with the two previous, is related to the quality of optical filters.

Remarkable work by USCB and Aurrion resulted in the hybrid integration of InP and Silicon material technologies [7]. The last column in Table I (after [7]) remarks all the required building blocks for MWP system can be built within this material technology, i.e. sources (DFB and Mode-locked lasers), amplifiers, electro-absorption modulators, all sort of passives (filters, couplers, polarization handling blocks…) as well as high speed photo-detectors [8], [9]. How this hybrid technology is of application to MWP is reviewed in [7], where the focus is not to beat traditional discrete component aggregation in MWP systems (on some aspects impossible, i.e. Watt operating fiber lasers, see below), but rather on exploiting novel systems concepts enabled by this hybrid integration scheme. Apart from the works by [7], other groups are pursuing the integration of gain media on Silicon technologies, and they have demonstrated amplifiers and lasers with Aluminium Oxide Erbium doped Silicon waveguides [10-12]. The active functions for the building blocks in Table I (laser, modulator and photo-detector) are subject to demanding requirements in a MWP system. The basic devices for signal generation in MWP systems are high power, low relative intensity and phase noise optical sources, and broadband linear external modulators. On-chip semiconductor lasers provide lower power values (300 mW) compared to watt-class Er-doped fiber lasers (3 W) but can feature very competitive performance in terms of RIN. For instance a InGaAlAs/InP quantum-well, high-power, low-noise packaged semiconductor external cavity laser (ECL) operating at 1550 nm has been recently reported [13] capable of providing 370 mW of fiber-coupled power with a linewidth of 1 kHz, and relative intensity noise -160 dB/Hz from 200 kHz to 10 GHz.

TABLE I
BUILDING BLOCK FEATURES AVAILABLE PER MATERIAL TECHNOLOGY[12]

	GaAs	InP	LiNbO3	Si(O)N, TriPleX	SOI	Hybrid InP/SOI
TL/BS	+++	+++				+++
PD	+++	+++			++	+++
MOD	++	++	+++		+	++
Passive	+	+	+	+++	++	+++
WPKG				+++	+++	+++
ELECT					+++	+++

Abbreviations: TL/BS= Tunable laser or broadband source, PD=Photo-Detector, MOD=Modulator, Passive=passive devices (couplers, filters, …), WPKG=Wafer level packaging, ELECT=Electronic System-on-Chip and System-in-Package integration. Silica on Silicon not shown, would excel in passive devices.

TABLE II
TECHNOLOGY FEATURES PER MATERIAL TECHNOLOGY [13]

	GaAs/ InP	LiNbO3	Si(O)N	TriPleX	SOI
Δn [%]	~10	~~5	<5	>25	>100
r_b [mm]	0.1	0.2	0.2-0.8	0.05	0.05
α [dB/cm]	2.5	0.2	0.05-0.3	0.01	<2
Transparency	NIR	NIR	VIS-NIR	VIS-IR	NIR
Fiber-chip coupling	-	+	+	+++	-
Function integration	++++	+++	+	+++	++
Fabrication cost	--	--	++	+++	++

Abbreviations: Δn=refractive index contrast, r_b=bend radius (related to overall circuit footprint), α=attenuation. IR=infrared, VIS=visible, NIR=near infrared. '+' good, positive, '-' worse, negative. Note Table I includes a Hybrid InP/SOI column not shown in this table, since the hybrid combination may benefit from the positive aspects of both technologies, shown in separated columns.

High RF power handling broadband linear external modulators have been reported in III-V semiconductor technologies. For instance, both electro-absorption (EAM) and Mach-Zehnder (MZ) modulators coupler with low noise (RIN<-160 dB/Hz) tunable sampled grating DBR InP lasers have been reported. EAM based transmitters have been reported featuring a dynamic range of 126.3 dB·Hz$^{4/5}$, while figures in excess of 115 dB·Hz$^{4/5}$ can be achieved for MZ transmitters. Both values are over the required with very low $V\pi$ values. For instance, in [14] an advanced semiconductor design with transfer substrate has been reported featuring a 0.3 volt V_π value, capable of handling a RF power of up to 200 mW and providing a modulation bandwidth in excess of 40 GHz. Finally, photo-detectors delivering high RF power are required in order to enhance the signal to noise ratio and dynamic range. Among the possible photo-detector design, the uni-travelling carrier (UTC) configuration exhibits high saturation current at high frequencies [15,16]. High power UTC detectors delivering up to 31.7 dBm (1.5 W) at a 3 dB bandwidth of 8 GHz have been reported [15]. Higher operating frequency UTC detectors have been demonstrated with 3 dB bandwidths in excess of 65 GHz and 15.9 dBm RF output power [16].

B. Functional devices

Regarding, functionalities that arise from the combination of building blocks, they may be classified resorting to a generic IMWP processor concept [17,18] in the following:

- Filtering

- Arbitrary Waveform Generator (AWG)
- Analog Digital Converter (ADC)
- Opto-Electronic Oscillator (OEO)
- Tunable Broadband Phase Shifter (TBPS)
- Tunable True Time Delays (TTTD)
- Instantaneous Frequency Measurement (IFM)
- Frequency Multiplication (FM)
- Optical Phase-Locked Loop (OPLL)
- Frequency Up/Down Converter (FU/DC)
- Radio-Frequency Transceiver (RFTRX)
- Beam-forming network (BFM)

For some of these functions, an excerpt of relevant works is provided in the following paragraphs, and summarized in Table III. For further details refer to [6][18].

Filters [19-21] have been produced in all the cited material technologies. In InP, filters have been reported with tunable central frequencies in the range of 10-40 GHz, and tunable bandwidths of 2-7 GHz, and at least 30 dB of stop band rejection. For lower RF frequencies, implementations have been reported in TriPleX technology, for the 2-8 GHz band, with bandwidths in 300-800 MHz and 60 dB rejection. Arbitrary Waveform Generators have been reported recently, with significant efforts in Ultra-wideband (UWB) generation. Reported in several material technologies (SiN, chalcogenide waveguides, InP and TriPleX) all are capable of generating FCC compliant signals for the 4-15 GHz band [22-25]. Tunable Broadband Phase Shifters and Tunable True Time Delays have been demonstrated mainly in Silicon technologies (SOI and TriPleX). TBPSs exhibit tunable phase shifts in the range of 0-90º in a 16-20 GHz bandwidth [26]. TTTDs provide tunable delays of up to 25 ps in 8 GHz [27] or up to 400 ps limited to 1 GHz bandwidth [28]. Instantaneous frequency measurement chips are reported in InP [29] and TriPleX technologies [30], featuring RF frequency determination ranges (RMS error) of 5-15 GHz (200 MHz) and 0.4-5 GHz (93.6 MHz). Optical-Phase Locked Loops with locking range in the (-9.5, 7) GHz range and locking bandwidth of 400 MHz have been reported in InP [31]. Finally, Beamformer chips have been demonstrated in TriPleX technology, capable of addressing 16 antenna elements, in the 2-10 GHz band, and with instantaneous bandwidth of 8 GHz [32].

Novel approaches

Some recent work has been reported proposing novel approaches to implement IMWP that are briefly described.

A. Graphene IMWP [33]

Graphene is a two dimensional single layer of carbon atoms arranged in an hexagonal (honeycomb) lattice that has generated considerable interest in recent years due to its remarkable optical and electronic properties. It has an energy versus momentum dispersion diagram where the conduction and valence bands meet at single or Dirac points. In the vicinity of a Dirac point, the band dispersion is linear and electrons behave as fermions with zero mass, propagating at a speed of light of around 106 m s^{-1} and featuring mobility values of up to 106 $cm^2V^{-1}s^{-1}$. These electronic properties make graphene a potential material for nanoelectronics and, in particular, for high-frequency applications. Graphene has noteworthy optical properties due to its conical band structure. Optical transitions include intra-band and inter-band transitions that contribute to its material conductivity. Depending on the value of its chemical potential that can be changed by changing the applied electrical voltage grapheme can behave as an electroabsorptive or an electrorefrective material. Exploiting either the electrorefractive or the electroabsortive behaviour of graphene lies at the heart of designing tunable photonics components in general and microwave photonic devices in particular. Furthermore, one of the main advantages brought by the use of graphene is that its band structure close to the Dirac points leads to an extremely high carrier mobility, enabling high-speed reconfiguration of its chemical potential with extremelly low energy consumption. For instance it has been anticipated that modulation speeds of up to 500 GHz with tens of femto joule energy consumption can be achieved.

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Graphene can be incorporated into silicon based integrated optic circuits using several configurations to implement graphene silicon waveguides (GSWs). One approach consists in placing a monolayer graphene sheet on top of a silicon bus waveguide, separated from it by a thin Al_2O_3 layer as shown in Fig. 1. Another option is to integrate two layers of graphene separated again by a thin Al_2O_3 layer on top of a silicon rib waveguide. In the so-called slot waveguides the graphene layer is sandwiched between doped silicon dielectrics.

In all the cases the presence of the graphene layer modifies the propagation characteristics (field profile, losses and effective index) of the guided modes and these can be in turn controlled and reconfigured changing the chemical potential by means of applying a suitable voltage

Fig. 2 illustrates, as an example, the design of a phase-shifter based on the deep GSW]. The structure is composed of two racetrack cavities rather than a single one in order to easily achieve a sharper transition in the phase transfer around the resonance frequency. The structure is designed for operation at 1550 nm featuring a cavity length of 213.6 µm which yields a free spectral range of 6 nm, enough for broadband operation of the phase shifter in the 20-100 GHz Rf frequency range. The resonator coupling constants are both equal to 0.12. Designs for true time delay lines, integrated gratings have already been reported and work is undergoing to provide their first experimental demonstrations,

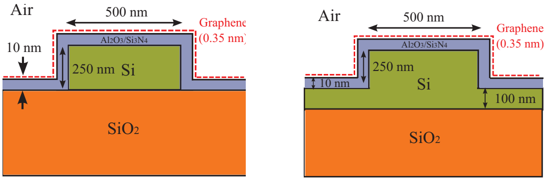

Figure 1. (Left) deep-etch and (Right) shallow-etch silicon waveguides with a layer of graphene placed on top of them

B. *Nonlinear IMWP* [34]

Incorporating optical nonlinearities in an IMWP processor has been recently proposed as a means to contruct general purpose MWP integrated signal processors. The rationale behind this approach is that many MWP signal processing functions can be generalized as processing of a number of copies of RF modulated optical signals using reconfigurable optical filters and nonlinear optical processes that create new optical wavelengths such as FWM, SFG, or DFG are attractive candidates for generating such signal copies. A high performance notch filter with unprecedented performance parameters in terms of signal rejection (51 dB), spectral tuning range (>30Ghz) and filtering resolution has been recently reported. It exploits the strong stimulated Brillouin scattering provided by a 6.5 cm highly nonlinear calchogenide waveguide. Work is being carried to exploit other nonlinear effects and, in ultimate term the feasibility of this approach will gratly depend on factors such as efficiency of the associated on-chip nonlinear processes, and the integrability of the nonlinear platform of choice with other optical functionalities such as optical modulation, reconfigurable optical filtering, and photodetection.

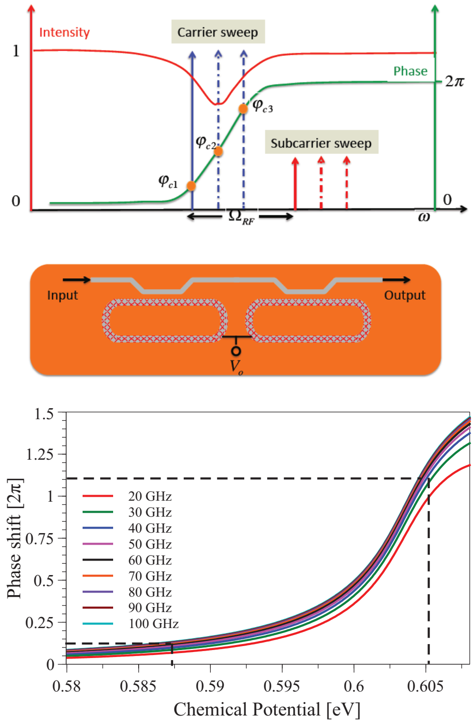

Figure 2. (Upper) principle of operation of a single-sideband microwave photonics RF phase shifter using an all pass optical filter resonance. (Intermediate) two-stage racetrack resonator GSW design of a tunable phase shifter . (Lower) impressed phase shift (modulus 2π) vs chemical potential.

Summary and Conclusions

We have reviewed some of the salient results in terms of technology, functionalities and future directions of Integrated Microwave Photonics. This emerging field is called to play a key role in enabling the widespread use of analog optical frontends that will be required in the radio-fiber interface of next generation fiber-wireless broadband networks.

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