Microwave Photonics: Current challenges towards widespread application

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Abstract: Microwave Photonics, a symbiotic field of research that brings together the worlds of optics and radio frequency is currently facing several challenges in its transition from a niche to a truly widespread technology essential to support the ever-increasing values for speed, bandwidth, processing capability and dynamic range that will be required in next generation hybrid access networks. We outline these challenges, which are the subject of the contributions to this focus issue.

OCIS codes: (060.5625) Radio frequency photonics; (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

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1. Introduction

Microwave photonics (MWP) [1–4] is a multidisciplinary field that brings together the worlds of radiofrequency engineering and optoelectronics. MWP brings a considerable added value to traditional microwave and RF systems as photonics allows the realization of key functionalities in these systems which are either are very complex or even not directly possible in the radiofrequency domain. Furthermore, it has succeeded in creating new opportunities for information and communication (ICT) systems and networks benefiting from the symbiosis of the optics and radiofrequency fields. This added value has been instrumental in attracting an increasing interest from both the research community and the industry over the last two decades.

While initially the research activity in this field was focused towards defense applications, MWP has expanded to address a considerable number of civil applications, including cellular [5], wireless [6], and satellite [7] communications, cable television [8], distributed antenna systems [9], optical signal processing [10] and medical imaging systems using terahertz (THz) waves [4] and optical coherence tomography techniques [11].

One of the main driving forces for MWP in the near and middle term future is expected to come from broadband wireless access networks [4] installed in shopping malls, airports, hospitals, stadiums, power plants and other large buildings. On top of this, the proliferation of tablet devices such as iPads, will exert further pressure for more efficient wireless infrastructures. Furthermore, it is also expected that the demand for microwave photonics will be driven by the growth of fiber links directly to the home and the proliferation of converged [12] and in-home networks [13].

Many of these novel application areas will demand ever-increasing values for speed, bandwidth, processing capability and dynamic range while, at the same time, will require devices that are small, lightweight and with low power consumption, exhibiting large tunability and strong immunity to electromagnetic interference. To cope with this growth scenario MWP has to address several challenges related to three strategic areas: 1) arbitrary microwave waveform generation and signal processing, 2) high-speed radio over fiber systems and 3) the integration of flexible MWP systems on a chip.

2. Arbitrary microwave waveform generation and signal processing

Microwave arbitrary waveforms are widely used in radar, communications, imaging, and warfare systems [14,15]. These are usually generated in the electrical domain using digital electronics. Due to the limited sampling rate, the generation of a microwave arbitrary waveform in the electrical domain is limited to a small time bandwidth product (TBWP). The challenge is to increase this figure. For many applications, however, microwave waveforms with a large TBWP are needed. Thanks to the high speed and broad bandwidth offered by optics, the generation of a large TBWP microwave waveforms in the optical domain has been considered a solution to this challenge. In general, photonic generation of microwave arbitrary waveforms can be implemented based on free-space optics [16,17], fiber optics [18,19], and integrated optics [20,21]. In a free-space-based system, a spatial light modulator (SLM), as a temporal or spectral shaper, is usually used. The advantage of using an SLM is the real-time updatability, which allows the generation of fast updatable microwave arbitrary waveforms. The limitation of a free-space-based system is the relatively large size and high loss, which could be avoided by using fiber optics. Fiber optics based microwave arbitrary waveform generation systems have been demonstrated with different architectures. One important component in a fiber-optic-based system is a fiber Bragg grating [22], which can be designed to have an arbitrary spectral response, allowing the generation a microwave arbitrary waveform. Recently, the generation of microwave arbitrary waveforms based on photonic integrated circuits (PICs) has been a topic of interest. Compared with a free-space or fiber-optics-based system, a PIC-based system has a much smaller size and better stability. For example, a microwave arbitrary waveform generator based on a silicon-photonic chip was demonstrated. The silicon-photonic chip consists of multiple ring resonators as a spectral shaper. The spectrum of the shaper could be controlled by means of thermal tuning of the embedded micro-heaters and frequency-chirped and other microwave waveforms were generated.

Photonic processing of microwave signals has also been a topic of interest and has been intensively investigated. The challenge here is to implement versatile, tunable and reconfigurable multiband structures featuring small size and low power consumption. The key advantages of processing a microwave signal in the optical domain are the high speed, wideband width and large tuning range, which may not be achievable by digital or analog electronics. Microwave signal processing functions implemented in the optical domain usually include filtering [23,24], differentiation [25] and integration [26], Hilbert transformation [27], mixing [28], and phase shifting [29]. These functions can be implemented based on free-space optics, fiber optics and integrated optics. For example, a microwave photonic filter can be implemented using an all-fiber [23,24] or an integrated [30] delay-line module with a finite impulse response. A differentiator and a Hilbert transformer can be implemented using a fiber Bragg grating (FBG) [25,26]. Recently, an all-optical integrator implemented based on a silicon photonic chip was demonstrated.

3. High speed mm-wave and radio over fiber systems

Millimeter-wave (mm-wave) based radio-over-fiber systems have been actively researched over the past two decades with the earlier work focusing on overcoming major transmission limitations and impairments including RF power fading due to fiber chromatic dispersion

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[31], intermodulation distortions arising from the nonlinearity of optical and millimeter-wave components [32], optical spectral efficiency and efficient generation of mm-wave optical carriers [33]. These works have resulted in the introduction of optical single sideband modulation scheme to combat the impact of fiber chromatic dispersion [34,35], optical carrier suppression modulation scheme for efficient generation of optical mm-wave signals [36], linearization schemes to improve the mm-wave radio-over-fiber link performance [37–39], and wavelength interleaving schemes to improve spectral efficiency [40,41]. However the research focus has changed over the last decade and has now shifted towards strategies to increase the wireless transmission data rate, which is the current challenge. This push is driven, as mentioned in section 1, by the unprecedented increase of affordable smart portable devices coupled with the high expectation of end users for seamless wireless connectivity.

To meet this future demand of multi-gigabits wireless data transmission, there are many different strategies that are being looked into for mm-wave radio-over-fiber scheme. The two main approaches to augment wireless data capacity are to increase the wireless spectral efficiency and to move to higher frequency wireless windows. Recently a lot of research on mm-wave fiber-wireless has targeted the W-band (75-110 GHz) to harvest the large amount bandwidth for meeting the high capacity wireless demand [42–49]. The transmission of 10 Gb/s on 120 GHz wireless signal, using simple amplitude-shift-keying (ASK) modulation has been demonstrated [44] and the capacity was further quadrupled by using advanced modulation format [46]. The race to push through the 100 Gb/s barrier for wireless data transmission has seen many different strategies being introduced. These schemes rely heavily on advanced modulation format with optical polarization multiplexing with MIMO configuration [47,48] to increase the degrees of freedom for transporting wireless data. The introduction of optical polarization multiplexing and MIMO has made truly ultra-broadband mm-wave radio-over-fiber technology feasible, which has seen demonstrations of >100 Gb/s wireless data transmission in the W-band in the recent times [47–49]. On the other hand, the use of optical polarization multiplexing the needs for coherent detection to be implemented within the antenna base stations, which may increase the cost and complexity of the base station architecture. Nevertheless the 100 Gb/s wireless data transmission breakthrough has opened up a new era for ultra broadband mm-wave radio-over-fiber technology with many issues to be solved and investigated.

4. Integrated circuits for microwave photonics

Up to date, 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 [1–3]. These configurations are bulky, expensive, power consuming and lack the desired flexibility. *Integrated Microwave Photonics* (IMWP) [50], which aims at the incorporation of MWP components/subsystems in photonic circuits, is an emergent area of scientific and technical research that is considered crucial for the implementation of both low-cost and advanced analog optical front-ends and, thus, instrumental to achieve the aforementioned evolution objectives.

IMWP is still in its infancy with sparse contributions being reported only recently which address either a very particular functionality or a limited set of devices. More specifically, efforts on the integration of MWP functionalities have been reported by several groups spanning III-V semiconductors [51], hybrid [52], silicon [53,54], and Si3N4 (TripleX) [55] technologies. In the context of filtering applications, most of the reported approaches are based on single and multiple cavity ring resonators. Other MWP functionalities have also been demonstrated by partially using integrated circuits. For example, broadband tunable phase shifters and true time delay lines have been reported based on cascaded SOA devices [56,57], passive silicon on insulator [58], and Si3N4 [59] optical rings, and passive III-V photonic crystal waveguides [60]. Primary attempts for arbitrary waveform generators have been recently reported in CMOS compatible silicon [61].

As a summary of the current state-of-the-art of integrated microwave photonics, the following limitations and challenges can be identified in this area:

a) The complete integration of any MWP functionality on a photonic chip has not yet been achieved or reported. This feature is highly desirable to benefit from the SWAP and cost advantages that integrated optics brings.

b) The implementation of the main MWP functionalities is contingent on the use of tunable dispersive optical delay lines, which are currently limited to optical fiber coils or Bragg gratings. A major scientific challenge is to design and fabricate integrated tunable MWP delay lines with the required low loss and high delay values. Some preliminary progress using Photonic Crystal waveguides has been recently reported [30,60], but a considerable work is still required.

c) The different applications demonstrated so far are generally based on very different circuit architectures with ad hoc designs, meaning that a particular circuit layout is designed for a particular functionality. A common architecture or *MWP transistor* with programmable functionalities would open the path towards medium and large-scale integration with unprecedented applications.

5. Concluding remarks

This focus issue presents a dozen papers reporting state of the art research results produced by internationally recognized research teams in the field of Microwave Photonics in the specific strategic areas outlined in the introduction and briefly developed in sections 2-4. The works provide an excellent sample of the current progress being achieved in addressing the main challenges and provide suitable information regarding the next steps to be taken in these directions.

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