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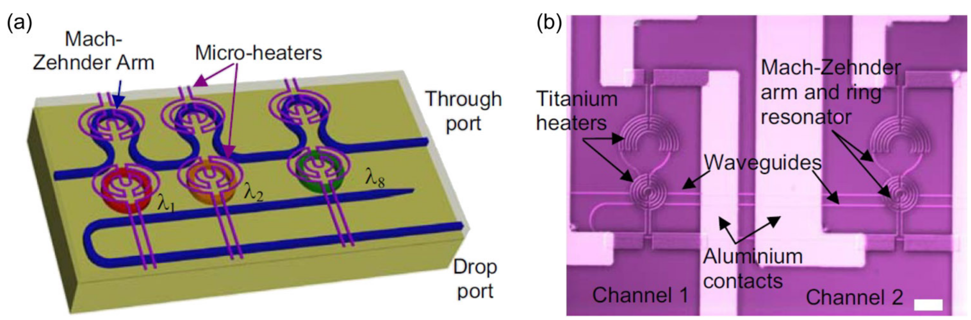

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Recent Breakthroughs in Microwave Photonics

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Abstract: We present a brief review of recent accomplishments in the field of Microwave Photonics (MWP). Recent research across a broad range of MWP applications is summarized, including photonic generation of microwave, millimeter, and Terahertz waves; broadband optical beamforming for phased array antennas; tunable, reconfigurable, and adaptive microwave photonic filtering, as well as the application of slow and fast light effects to the implementation of tunable microwave phase shifting and true time delay operations.

Index Terms: Microwave photonics, photonics generation, microwave photonic filtering, optical beamforming, slow and fast light.

Significant worldwide advances have been achieved in 2010 in a wide range of Microwave Photonics (MWP) applications, spanning different technology platforms, including integrated photonics based on III–V technologies and silicon-on-insulator (SOI), as well as photonic crystals (PC). In this sense, integrated MWP is of strategic importance as it opens the door for MWP to benefit from potential low-cost approaches, reliability, and economies of scale.

The first main area in which important progress has been reported is ***photonic generation*** of microwave, millimeter, and terahertz waves. An impressive advance regarding integrated MWP is reported in [1], where an ultrabroad-bandwidth arbitrary radio frequency generator based on a silicon photonic spectral shaper has been presented, that is capable of synthesizing burst radio-frequency waveforms with programmable time-dependent amplitude, phase, and frequency tunability up to 60 GHz. The generator is based on the wavelength-to-time conversion of the broad spectrum of a mode-locked pulsed laser which has previously been shaped by a photonic integrated circuit (PIC) consisting in eight independent ring resonators (RRs), as shown in Fig. 1. By independently thermo-optical tuning the spectral characteristic of every RR, the broadband spectrum of the mode-locked laser output is carved, and this characteristic is translated to the time domain using a dispersive element. By replacing the output couplers of the RRs with tunable Mach–Zehnders (MZM), the amplitude of the bandpass can be programmed, providing full amplitude and wavelength tunability of the resonances comprising the shaped spectrum and, therefore, the time characteristics of the burst signal. Two interesting figures of the described chip are worth mentioning: footprint of 0.1 mm $\times$ 1.2 mm on an SOI platform and 25 dB of total optical fiber to fiber loss.

Still within the field of millimeter-wave generation, three high-data-rate demonstrations employing bulk optical components have presented in [2]. The first option is based on two cascaded MZMs for optical double-sideband suppressed carrier 60-GHz generation and subsequent broadband on–off

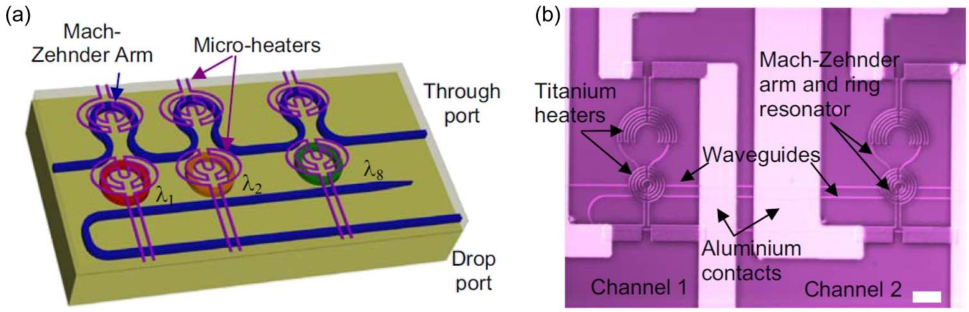

Fig. 1. Attenuation control in an ultrabroad-bandwidth arbitrary radio-frequency generator based on a Silicon Photonic spectral shaper. (a) Mach–Zehnder arms incorporated in the through port near the rings. (b) Optical image showing two sets of finished RRs with microheaters and contact pads. Scale bar is 20 μm.

keying (OOK) modulation up to 12.5 Gb/s with a spectral efficiency of $\sim$0.5 bit/s/Hz. The sensitivity of the constructed coherent wireless receiver with 23-dBi horn antennas is above -46 dBm for error-free transmission of 10.3125 Gb/s in an outdoor environment over a wireless distance of 50 m. To improve the spectral efficiency, a second option based on orthogonal frequency-division multiplexing (OFDM) using 16 quadrature amplitude modulation (16QAM) has been proposed, achieving a wireless transmission of 27.04 Gb/s over an air link of 2.5 m. A third option, which is made up by a compact and cost-effective 60-GHz wireless transmitter comprising a mode-locked laser diode and an electroabsorption modulator, accomplishes error-free indoor and outdoor 5-Gb/s wireless transmission over distances up to 40 m.

A new technique for generating narrow-linewidth microwave signals has been recently presented in [3]. It is based on beating multiple signals by using coherence control of a time-delayed and frequency-shifted optical signals comb. Microwave signal generation at 11.25 and 30 GHz with a linewidth less than 100 Hz and sideband suppression $>$ 30 dB has been demonstrated.

Within the area of optoelectronic oscillators, a simple method to extend the frequency tunability has been recently reported in [4]. The system core is a Fabry–Perot laser diode which functions through external injection as a high-Q photonic microwave filter. The generated frequency is tuned over the operational bandwidth of an electrical amplifier (from 6.41 to 10.85 GHz) by changing the optical wavelength and tuning the electrical phase shifter. More than 20 dB of second harmonic suppression and a phase noise of -92.8 dBc/Hz at a 10-kHz offset frequency have been demonstrated.

Optical phased-locked loops (OPLLs) constitute another interesting approach where some analog MWP functions can be greatly improved. The main advantage stems from the fact that, by reducing the path lengths, higher loop bandwidths can be achieved, while at the same time, very stable optical paths that allow low-noise coherent summing of optical signals are feasible. Some interesting preliminary results are reported in [5] with special emphasis on PIC-based OPLLs for coherent receivers for phase-modulated signals and phased-locked tunable lasers. A fundamental 20-GHz offset locking and 300-MHz bandwidth have been demonstrated, and a phase-error variance $\sim$0.03 rad^2 was measured over a 2-GHz measurement window.

Terahertz wave generation is an emergent field of interest within MPW due to its potential advantages in material characterization, nondestructive testing, tomography imaging, and chemical or biological sensing. In this context, the European project Integrated photonic millimeter-wave functions for broadband connectivity (IPHOBAC) in relation to the interesting results achieved by consortium members in 2010, such as the development of a waveguide-fed, traveling-wave uni-traveling carrier photodiode (TW-UTC-PD) [6], is worthy of mention. This device, integrated with different types of antennas, has been demonstrated as a tunable terahertz source covering frequencies up to 1 THz. Some promising results are narrow-band output powers of 148 μW at 457 GHz and 24 μW at 914 GHz for devices integrated with resonant antennas, while there is also 105 μW at 255 GHz down to 10 μW at 612 GHz for devices integrated with broadband antennas.

Furthermore, the application of the frequency modulation (FM) technique is one of the most promising solutions for measuring distances in noninvasive imaging systems, as it has been reported in [7], where the FM of a 350-GHz signal with a 6.7-GHz frequency deviation was experimentally demonstrated. In this sense, the work initiated in 2009 about serial time-encoded amplified microscopy (STEAM) technology [8] should also be mentioned. By means of optical image amplification, STEAM overcomes the fundamental tradeoff between sensitivity and speed that affects virtually all optical imaging systems.

The second main MWP area where significant advances have been recently reported is ***photonic signal processing***. This area embraces solutions for optical beamforming, photonic filtering, microwave phase shifting, and discriminators for phase-modulated links.

A novel integrated optics approach for optical beamforming has been reported within the framework of the Smart antenna systems for radio transceivers (SMART) Dutch project [9], [10]. A nonplanar phased array antenna has been developed which consists of broadband K_u-band stacked patch antenna elements and a broadband optical beamformer network (OBFN) that employs optical RRs, integrated in low-loss complementary metal–oxide semiconductor compatible waveguide technology. The proposed OB is tunable and can operate in squint-free mode (that is, based on true time delays and not in tunable phase shifters). The broadband true time delay feature is achieved by a subsystem based on coherent optical combining using cascades of optical RRs as tunable elements. A prototype based on eight elements was implemented featuring an optical sideband suppression of 25 dB, RF-to-RF delay up to 0.63 ns, a tuning speed of 1 ms, and a phase accuracy better than pi/10 rad in a range of 1–2 GHz.

As far as microwave photonic filtering is concerned, several groups have reported interesting results supported by different optic platforms. A recent reconfigurable approach [11] has implemented a filter that is switchable between high Q bandpass and notch responses by tuning two tunable optical bandpass filters (TOBFs). Positive and negative coefficients are obtained easily by detuning the TOBF to get phase-intensity signal conversions in phase or out of phase. A free spectral range (FSR) of 4.9 MHz and Q factor of 327 has been accomplished, while a rejection ratio of 42 and 34 dB was achieved for the bandpass and notch filters, respectively. The operation frequency, which is limited by the shape and bandwidth of the TOBFs, was located around 20 GHz.

Integrated-optics filtering led to various preliminary results based mainly on single-cavity RRs. For instance, [12] reports the results for a unit cell that could be an element of more complex lattice filters. This unit cell, which is integrated in InP-InGaAsP, is composed of two forward paths and contains one RR. By selectively biasing one semiconductor optical amplifier (SOA) and phase modulators placed in the arms of the unit cell, filters with a single pole, a single zero, or a combination of both can be programmed. In particular, for the design reported in [12], the frequency tuning range spans around 100 GHz. The same group is now working on more complex designs and different unit cell configurations [13]. A hybrid version incorporating silicon photonic waveguides was recently reported [14]. Another more complex scheme has also been recently presented [15], where 1–2 GHz-bandwidth filters with very high extinction ratios ($\sim$50 dB) have been demonstrated. With a power dissipation of $\sim$72 mW, the ring resonance can be tuned (thermal control) by one free spectral range, resulting in wavelength-tunable optical filters. Both second- and fifth-order RRs have been demonstrated.

The impressive potential of photonic crystals is stimulating, in the context of MWP as well, the interest of researchers. The feasibility of exploiting PCs with the aim of implementing MWP filtering is demonstrated in [16]. Specifically, a design of a 2-D PC asymmetric Mach–Zehnder filter based on self-collimation effect is reported. Self-collimated beams, that is, diffraction-free beams, are effectively steered by employing line-defect beam splitters and mirrors in order to create the interferometric structure. Reflection-related problems at the input and output ports, which causes crucial performance limitations when using self-collimation, are minimized by adding antireflection layers. A full tunability over the FSR bandwidth of the notch response is controlled by acting on the geometrical properties of the defects periodical structure.

The implementation of tunable phase shifting functionalities is also of great importance in many MWP applications. Several approaches using different technologies have already been presented in the literature. Within the integrated optics approach, a tunable microwave phase shifter based on SOI dual-microring resonator has been recently demonstrated [17]. A quasi-linear phase shift of 360° with RF-power variation lower than 2 dB at a frequency of 40 GHz is achieved. The phase shift is electrically controlled by means of two independent microheaters, which are used to alter the silicon effective index for FSR adjustment purposes, giving, as a result, phase-shifting tunability.

A novel method enabling high-accuracy full characterization of subpicosecond optical pulses based on temporal interferometry by means of an unbalanced temporal pulse shaping has been demonstrated in [18]. Since no fiber interferometer is used, the system stability is greatly improved. In addition, the temporal interference pattern can be tuned by acting on the microwave modulation signal, which allows testing a wide variety of input pulses. The feasibility of characterizing $\sim$550-fs width optical pulse train with a repetition rate of 48.6 MHz is demonstrated using this approach.

In addition, the recent demonstration of the first integrated discriminator for phase-modulated MWP links [19] is worth mentioning. The photonic chip consists of five optical RRs, where a drop-port response of an optical ring resonator (ORR) is cascaded with a through response of another ORR to yield a linear-phase-to-intensity-modulation conversion. The balanced link exhibits high second- and third-order intercept points of 46 and 36 dBm, respectively, which are simultaneously achieved at one bias point.

Finally, we briefly state some of the most remarkable advances recently accomplished within our research group at the ITEAM Research Institute of the Universidad Politecnica de Valencia. The subarea of arbitrary waveform generation led to the proposal of a novel photonic structure based on a microwave photonic filter fed by an optical source with a reconfigurable power spectral distribution, a dispersive element, and the combination of an interferometric structure with balanced photodetection [20]. This configuration provides a large degree of flexibility, in contrast with other optical techniques, since the generated waveform, which reaches operation frequencies up to 15 GHz for bandwidths from 1 to 8.75 GHz, can be fully reconfigured by controlling the optical source power spectrum and the interferometric structure. In order to show the system potentialities, the waveform generator was adapted to multiband ultra-wideband (UWB) signaling format.

The application of slow and fast light (SFL) effects to the implementation of both microwave tunable phase shifting and true time delay functionalities has been another field of intense research. Important results have been obtained in the framework of the European project Governing the speed of light (GOSPEL) which are applicable to phase array antenna systems and dynamically reconfigurable filters. For the purpose of achieving true time delay, a novel scheme based on the combination of phase shifting and stimulated Brillouin scattering (SBS) in fibers, which exploits the separate carrier tuning technique on narrowband resonances, was reported in [21]. The spectral shape of a complex-valued two-tap filter (with a bandwidth of 120 MHz at a central frequency of 6 GHz) was shifted by making use of the SBS frequency tuning, allowing an FSR change regarding the fractional bandwidth on the order of 20%. A tunable 360° MWP phase shifter, based on the exploitation of coherent population oscillations in active semiconductor waveguides, was demonstrated in [22] for a broad frequency range up to 40 GHz. The proposed phase shifter is based on the cascading of several SOAs, with in-between stages of optical filtering and regeneration, and can be reconfigured on a sub-nanosecond time-scale.

MWP remains as one of the most active and multidisciplinary research fields within the photonics community. Significant activity and progress have recently been made in the areas of photonic generation and processing of microwave, millimeter, and terahertz waves, providing many advantageous features over their electronic counterparts. Among the different technology platforms reported last year, integrated photonics has gained special prominence, as compared with discrete components, and will be expected to experience an increasing impact in future years.

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