Microwave photonics combines two worlds

Microwave photonics, which 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 and is set to have a bright future. The technology makes it possible to have functions in microwave systems that are complex or even not directly possible in the radiofrequency domain and also creates new opportunities for telecommunication networks. Here we introduce the technology to the photonics community and summarize recent research and important applications.

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Microwave photonics (MWP) has been defined as the study of photonic devices operating at microwave frequencies and their application to microwave and optical systems[1–3]. Its initial rationale was to use the advantages of photonic technologies to provide functions in microwave systems that are very complex or even impossible to carry out directly in the radiofrequency (RF) domain. But MWP is also succeeding in incorporating a variety of techniques used in microwave engineering to improve the performance of photonic communication networks and systems.

Figure 1 shows a schematic highlighting the fundamental concept of a simple microwave photonic link. One or more analog electrical signals at a microwave frequency are transported over an optical fibre or photonic link, with electrical-to-optical and optical-to-electrical conversion at the transmitting and receiving side, respectively, of the photonic link. The key advantages of microwave photonic links over conventional electrical-transmission systems, such as coaxial cables or waveguides, include reduced size, weight and cost, low and constant attenuation over the entire microwave and millimetre-wave modulation frequency range, immunity to electromagnetic interference, low dispersion and high data-transfer capacity. The weight and attenuation benefits of microwave photonic links over coaxial cables are particularly compelling: typically 1.7 kg km^{-1} and 0.5 dB km^{-1} for fibre with 567 kg km^{-1} and 360 dB km^{-1} at 2 GHz for a coaxial cable.

Our aim here is to introduce MWP to the general photonics community. For that purpose we review the basic concepts and historical developments behind MWP, describe its main technologies and field of applications, and also report on some of the most notable research results obtained in recent years. We conclude by discussing our perspective on the future prospects and challenges for MWP.

In many aspects the historical development of MWP runs in parallel with the field of optical communications. According to Alwyn Seeds at University College London, the development of the first semiconductor lasers and electro–optic modulators suitable for gigahertz modulation in the 1970s, the availability of low-loss silica multimode and single-mode optical fibres, and the development of fast depletion p–i–n and avalanche detectors giving useful microwave bandwidth response, are three of the fundamental historical developments in MWP[2].

Since the early experiments during the late 1970s, the field of MWP has expanded to address a considerable number of applications including high-performance analog microwave photonic fibre links for antenna remoting in radar systems, microwave photonic links for cellular, wireless, satellite and radio-astronomy applications, cable television systems, optical signal processing and high-speed optical packet switched networks. Some of these applications can be considered as commercially established (for instance, high-performance microwave photonic links have an annual sales market[3] above \$100 million), whereas others are still in a phase of research and development.

DEVICES AND MATERIALS

The fundamental elements of a microwave photonic link are devices that offer signal modulation, or control, or detection at very high frequencies. Since the first semiconductor laser was invented, much progress has been made in creating lasers that can be directly modulated at microwave and even millimetre-wave bandwidths. The modulation bandwidth of a semiconductor laser is an intrinsic parameter set by the relaxation resonance frequency of the device, which depends on a number of factors, including photon lifetime, differential gain, carrier recombination time and optical output power. The achievement of high direct modulation bandwidths requires an optimization of both the internal structure of the semiconductor laser and the design of the laser package because electrical parasitics associated with the laser chip and package will also limit the frequency response[4].

Well over a decade ago[5], efforts commenced to increase the direct modulation bandwidth of semiconductor lasers through the incorporation of quantum wells and the addition of strain in the semiconductor material. Since then, 1.55-μm InGaAsP quantum-well semiconductor lasers operating at frequencies greater than 30 GHz have been demonstrated[6]. Another approach

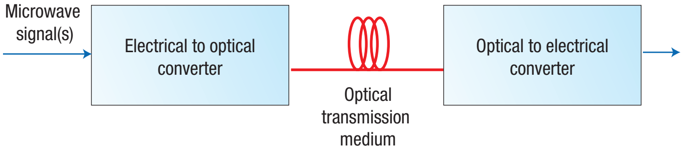

Figure 1 Schematic highlighting the fundamental concept of an analog microwave photonic link. One or more microwave signals are converted into the optical domain before transmission through a photonic or optical fibre link. At the other end of the photonic link, the signal is converted back into the electrical domain.

to increasing the laser modulation bandwidth is to enhance the frequency response resonantly, using external cavity lasers[7] or monolithic multisection lasers[8]. Using such techniques, narrow transmission windows at millimetre-wave frequencies have been achieved. Recently a multisection, 1.55-μm distributed Bragg reflector laser incorporating a coupled-cavity injection-grating design was reported[9], with an intrinsic 3-dB modulation bandwidth of 37 GHz. The principle behind this device is to extend the length of the laser cavity, thereby increasing the photon round-trip time and enabling the photon–photon resonance to interact with the electron–photon relaxation oscillation.

Optical injection locking is another technique that enhances the resonance frequency of semiconductor lasers[10]. Using such a scheme, researchers at the University of California (UC), Berkeley, have demonstrated a 72-GHz resonance frequency using a 1.55-μm InGaAsP distributed-feedback (DFB) laser injection-locked to an external cavity diode laser[11]. Other UC Berkeley researchers are also using strong optical injection locking to enhance the resonance frequency of semiconductor lasers, and have reported a 50-GHz resonance frequency in an optically injection-locked 1.55-μm vertical-cavity surface-emitting laser (VCSEL)[12]. Under free-running conditions the VCSEL showed a relaxation resonance of only 7 GHz.

The development of large-bandwidth external modulators has also seen intense investigation over the past two decades. For their practical application in MWP systems, it is imperative that these devices feature the characteristics of broad bandwidth, low drive voltages, good linearity, bias stability, high optical power-handling ability and low optical insertion loss. To give the required electro–optic effect in an external modulator, materials such as lithium niobate, semiconductors or polymers can be used, and travelling-wave interferometric structures are generally used to achieve a broad frequency response.

There have been a number of demonstrations of lithium niobate interferometric modulators with bandwidths in excess of 40 GHz and relatively low drive voltages[13,14]. Through special design of the modulator electrode structure to incorporate a ridge waveguide, 3-dB electrical bandwidths of 30 and 70 GHz with drive voltages of 3.5 V and 5.1 V, respectively, have been achieved[14]. Several examples of broadband electro–optic modulators based on semiconductor materials have also been reported[15,16]. Although these devices have bandwidths in excess of 30 GHz, their drive voltages are rather high (over 10 V at 40 GHz) because of the relatively low bulk electro–optic coefficient of semiconductor materials as well as a poor overlap of the applied electric field and the optical mode. The fibre-to-fibre coupling loss of such modulators also tends to be high (up to 10 dB) compared with lithium niobate devices (typically less than 4 dB).

Organic polymers have several attractive features for integrated optical applications and can be made electro–optic using high-temperature poling methods. Several broadband electro–optic polymer modulators have been developed[17] with bandwidths and drive voltages similar to their semiconductor counterparts, but problems associated with this technology remain, namely the power-handling capacity and the long-term bias stability.

Electro-absorption modulators (EAMs) are made from III–V-compound semiconductors and are either based on bulk semiconductor materials incorporating the Franz–Keldysh effect or make use of quantum-well structures to give the quantum confined Stark effect. Electro-absorption modulators based on quantum-well structures[18] have displayed bandwidths in excess of 40 GHz with drive voltages of less than 4 V. Because of free-carrier absorption and band-to-band absorption, however, the optical propagation loss of an EAM is large, typically 15–20 dB mm^{-1}, restricting the size of the device to less than several hundred micrometres. As a result EAMs are considered as lumped-element components and their speed of operation determined by the resistance × capacitance time constant of the circuit. Bandwidths in excess of 60 GHz can be achieved by lowering the terminating resistance of the EAM, but this comes at the expense of a higher drive voltage[19], although travelling-wave techniques can potentially lower the required drive voltage and improve the extinction ratio[20]. Electro-absorption modulators typically suffer from relatively poor optical power-handling capabilities and are also very sensitive to wavelength and temperature changes, so strict bias control is necessary during operation. A key advantage, however, is their ability to be directly integrated with semiconductor lasers, and a travelling-wave electrode EAM integrated DFB laser with a bandwidth in excess of 50 GHz was recently reported[21].

For the detection of optical signals in MWP systems, photodetector technologies with high responsivities, bandwidths and optical power-handling capability are required. The photodetector bandwidth is ultimately limited by both internal transit-time considerations and extrinsic factors, such as electrical parasitics. High-speed photodetectors operating in the range 1.3–1.55 μm have been reported based on surface-illuminated or vertically illuminated techniques with 3-dB bandwidths greater than 110 GHz being achieved[22]. Surface-illuminated photodetectors, however, suffer from an inherent trade-off between bandwidth and device efficiency. The edge-illuminated waveguide photodetector is one device structure that has been demonstrated as being able to achieve both a large bandwidth and efficiency; a 45-GHz 3-dB bandwidth and 90% internal quantum efficiency at 1.55 μm has been reported[23]. By also designing the waveguide photodetector to be a ‘travelling-wave’ type, where photon absorption occurs in a distributed manner along the length of the device, the parasitic bandwidth limitations can be reduced, and a bandwidth of 172 GHz has been reported[24].

High-frequency photodetectors with high saturation powers and large electrical output powers are also very useful in certain MWP applications. The saturation power is limited by the nonlinearity of the photodetector response, which is caused by a decrease in the electric field and a reduction in the carrier velocity due to a space–charge effect. A photodetector structure that can overcome the drawback of a low saturated carrier velocity is the uni-travelling-carrier photodetector (UTC-PD) developed by NTT Electronics almost a decade ago[25]. In the UTC-PD only electrons travelling at a velocity much higher than the saturation velocity contribute to the space–charge effect, and consequently very high output photocurrents can be achieved. In addition, the UTC-PD can be designed to give a very high frequency of operation because the depletion layer thickness is independent of the absorption layer thickness. A UTC-PD with a bandwidth of 94 GHz and peak photocurrent of 184 mA has been reported[26], and more recently high-output-power UTC-PD modules with waveguide output ports have been developed for even higher-frequency operation[27], extending beyond 300 GHz.

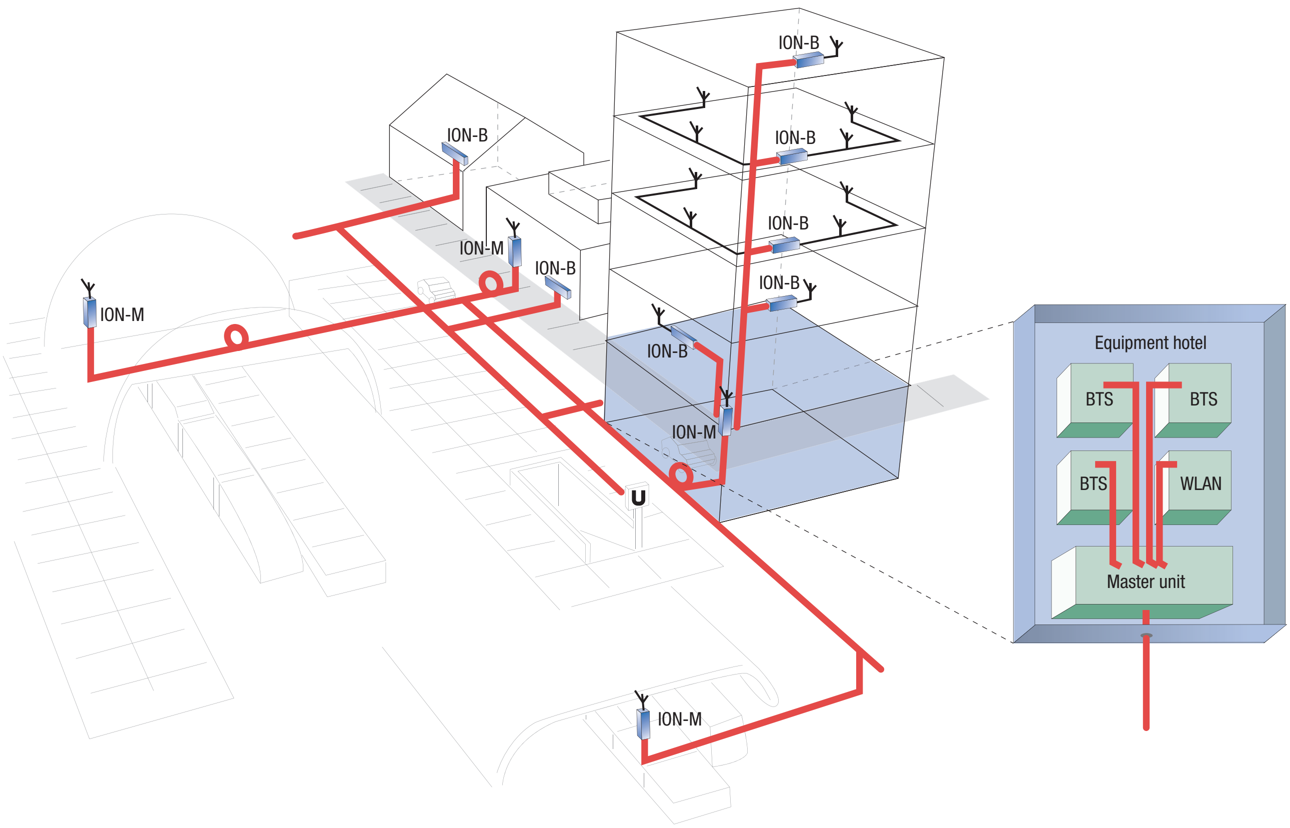

Figure 2 A schematic showing an example of a commercially available HFR system: Andrew Corporation's ION (intelligent optical network) family of optical distributed antenna systems. (BTS: base transceiver station; ION-B: formerly Britecell ; ION-M: formerly MMRI)

Other devices that may have potential applications in MWP systems are microwave devices that can be controlled using optical signals, including amplifiers, oscillators, switches and mixers. Here carriers are photogenerated directly within the microwave device by the incident optical signal, thereby changing the device capacitance or increasing the conductivity of the semiconductor material. The study of optically controlled microwave devices began over two decades ago with a view to their potential application in optical phased-array radars (a good overview can be found in ref. 28), but there have been fewer developments over recent years.

RADIO-OVER-FIBRE SYSTEMS

One of the main applications of MWP technologies is the transport and distribution of radio or wireless signals over optical fibre[29] — an area of intense research and investigation over the past 20 years. The integration of fibre-optic and wireless networks form what is often referred to as a hybrid-fibre-radio (HFR) system, which has become an essential technology for the provision of untethered access to broadband wireless communications. Its uses include last-mile solutions, improvement of radio coverage and capacity, and backhaul of current and next-generation wireless networks. The transport of a number of modulated radio signals over optical fibre in an HFR system is very similar in concept to the delivery of video signals in optical fibre-cable television systems, which use subcarrier multiplexing to combine multiple video signals in the RF domain for transmission over fibre by a single wavelength[30].

The advantages of optical fibre as a transmission medium make it the ideal solution for efficiently transporting radio signals from a central office to remotely located antenna sites. One of the key benefits of radio-over-fibre systems is that they allow a flexible approach for remotely interfacing to multiple antennas, with the ability to reduce system complexity by using a centralized architecture that incorporates a simplified antenna module located closer to the customer. By allowing centralized control over a large geographical area, HFR systems can support large fluctuations in traffic load through the provision of dynamic-channel-allocation capabilities[31]. Hybrid-fibre-radio technologies also provide a 'future-proofing' capability where by proper design, multiple radio services and standards can be accommodated. The types of wireless systems where HFR technology is now being used include cellular networks, indoor distributed antenna systems and wireless local area networks (WLANs), as well as fixed and mobile broadband networks that can provide very high bandwidth services to users.

Hybrid fibre radio is now well and truly a commercial reality for indoor applications in the form of distributed antenna systems as well as outdoor wireless systems. An example of a commercial HFR system manufactured by Andrew Corporation for indoor wireless signal distribution[32] is shown in Fig. 2. This optical distributed antenna system (the ION) provides uniform radio coverage and is capable of transporting a variety of radio signals at frequencies ranging from 800 to 2,500 MHz, covering cellular and WLAN applications. This particular system has recently been deployed at a number of important sporting events, including the 2000 Olympic Games in Sydney, Australia, and the 2006 International Football Association World Cup held in Germany[32].

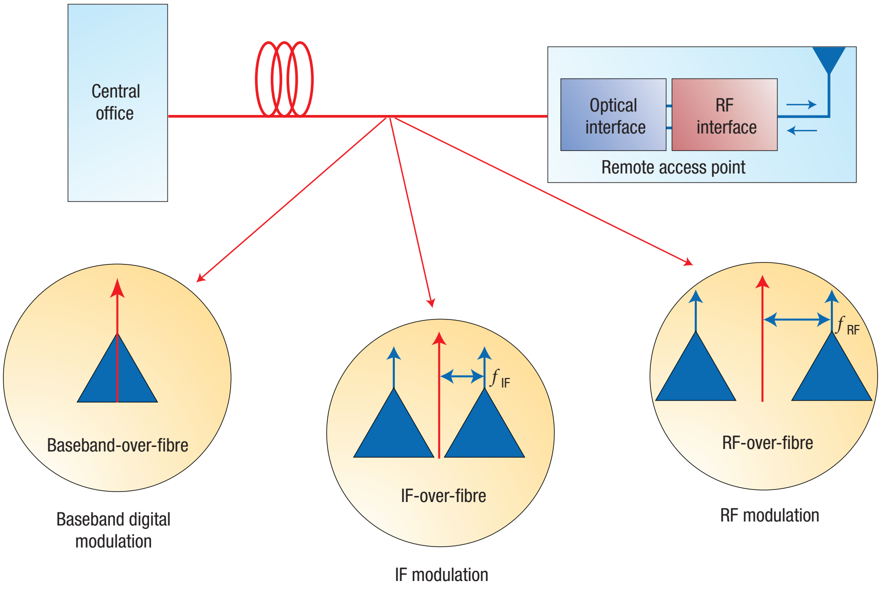

Figure 3 Schematic highlighting three possible schemes for radio signal transport between the central office and remote access point in HFR systems. The typical optical spectrum is shown in each case: baseband-over-fibre, intermediate-frequency(IF)-over-fibre and RF-over-fibre. (f_{IF} and f_{RF} denote the values of the intermediate and radio frequencies respectively.)

Technical challenges for the HFR systems are the development of suitable technologies and architectures for efficient conversion and distribution of the radio signals, while reducing the complexity of the hardware located at the remote antenna site. This is particularly important for wireless systems operating in the millimetre-wave frequency range, where the deployment of HFR systems will require the installation of a larger number of antenna modules. The radio environment also sets key requirements for the HFR system, including the spurious free dynamic range of the link, which defines the usable dynamic range before spurious noise interferes or distorts the fundamental signals. Ultimately there is a trade-off between the complexity of the electronic/RF and the optoelectronic interfaces in the central office and the antenna unit.

There are several possible approaches to transporting radio signals over optical fibre, as shown in Fig. 3, each with certain trade-offs. In an RF-over-fibre transport scheme the radio signals are transported directly over the fibre at the wireless transmission frequency, without the need for any subsequent frequency up- or down-conversion at the remote antenna sites. Radiofrequency-over-fibre signal transport for HFR systems operating at cellular and WLAN systems (<5 GHz) can be readily achieved through the direct modulation of high-linearity single-mode DFB lasers. However, recent work has demonstrated the ability to use low-cost directly modulated uncooled DFB lasers[33], as well as shorter-wavelength VCSELs transmitting over multimode fibre (MMF)[34,35]. Both intermediate-frequency-over-fibre, and baseband-over-fibre HFR transport schemes can readily make use of mature and reliable RF and digital hardware for signal processing at the central office and remote antenna site as well as low-cost optoelectronic interfaces. But the need for frequency conversion complicates the antenna module architecture design, particularly as the wireless network frequency increases. The additional hardware required at the antenna site can also limit the upgradability of the HFR system.

For wireless networks operating at higher frequencies, such as picocellular systems at 38 GHz and wireless personal area networks (WPANs) in the 60-GHz band, RF-over-fibre transport becomes less straightforward. Such HFR architectures require suitable high-speed optical modulation techniques that can generate millimetre-wave modulated optical signals as well as high-speed photodetection techniques. A key issue also arises from the increased impact of fibre chromatic dispersion, which can introduce a considerable power penalty on the detected RF carriers. Considerable research effort has been devoted towards developing RF-over-fibre transport schemes that are either dispersion-tolerant[36,37], such as optical single sideband modulation[36], or based on dispersion compensation techniques commonly used in optical networks, such as chirped fibre Bragg grating (FBG) filters[38,39].

Early demonstrations of millimetre-wave HFR systems were mainly proof-of-concept half- and full-duplex transmission experiments, which demonstrated a variety of techniques for the optical generation and transport of modulated millimetre-wave signals[40–47], including optical heterodyne[40], harmonic up-conversion using mode-locked lasers[45] and RF-over-fibre with a single EAM dual-function transceiver at the antenna site[46], as well as baseband-over-fibre with remote delivery of the local oscillator signal[43]. Researchers from Alcatel, Germany[48], and Communications Research Laboratory, Japan[49], also carried out field trials, which extended the laboratory demonstrations to real radio propagation environments.

Technologies for millimetre-wave HFR systems continue to be actively investigated, particularly at 60 GHz for potential WPAN applications. For example, researchers are exploring the use of new devices, such as millimetre-wave opto-electronic mixers for frequency conversion to or from an intermediate frequency[50], and are studying wavelength division multiplexing (WDM) in HFR systems as a means of increasing network capacity[51–53]. To take advantage of the existing WDM infrastructure as much as possible and allow cost-effective HFR network deployments, it is essential that such networks can be merged and integrated with conventional WDM technologies. The merging of HFR systems with other types of access networks, such as FTTH (fibre-

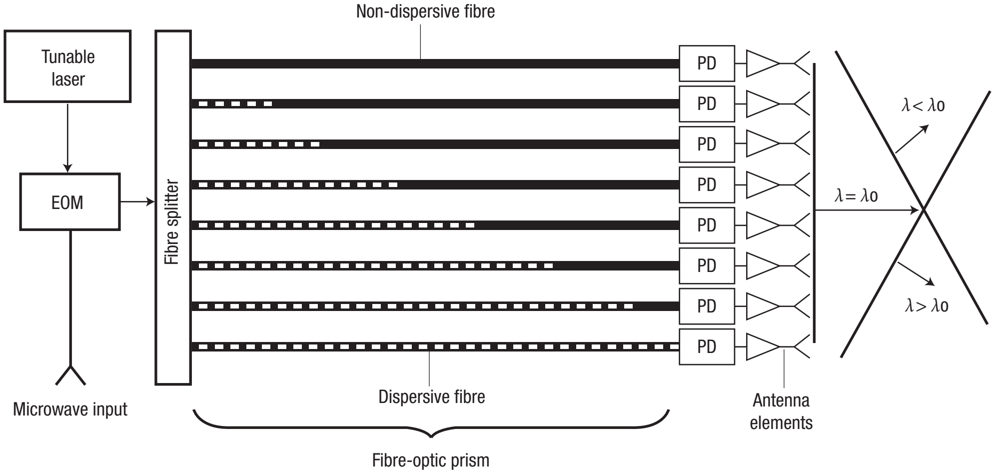

Figure 4 Schematic showing a fibre-optic prism with a single laser to feed numerous phased-array elements[68]. A true time-delay feed is formed by splitting the optical carrier into a fibre-optic prism, created by connecting varying amounts of highly dispersive and non-dispersive fibre. At a central wavelength, λ_0, the main antenna beam is directed broadside, whereas at wavelengths less (greater) than λ_0, each of the prism fibres adds (subtracts) a time delay proportional to its dispersion, resulting in element phasing such that the main antenna beam is steered towards (away from) the non-dispersive fibre side. (PD: photodetector; EOM: electro–optic modulator.) Reproduced with permission from ref. 68. Copyright (1993) IEEE.

to-the-home), is also being explored, leading to transparent heterogeneous access architectures[54–56].

New concepts for simplifying the antenna-module architecture are also being explored. The concept of a completely passive antenna access point based on the use of a single EAM for HFR systems operating at frequencies below 2 GHz was demonstrated a decade ago[57]. Since then, the use of a single electro-absorption transceiver in a 60-GHz HFR system has been demonstrated[58] and a variety of techniques have been reported[59,60] for re-using the optical carrier to avoid the need for an expensive high-performance laser at the antenna site. Most recently, the transmission of ultrawideband (UWB) signals in HFR systems is being investigated owing to the emergence of new WPAN standards[61].

OPTICAL BEAM FORMING

One of the earliest applications of MWP technology was the use of optical-fibre networks for distributing signals, as well as beam forming in phased-array radar systems. Phased-array antennas work on the principle that by controlling the relative phase of an RF signal between successive radiating elements of an antenna array, a beam can be created that will radiate in a specific direction. A beam-forming network is then used to create the required phase shifts at the antenna inputs. The operating frequencies for these systems can extend from the lower microwave region up into the millimetre-wave band.

Optical fibre offers considerable potential for replacing the bulky, heavy and lossy coaxial cable or waveguide feed networks in phased-array radar systems. Optically controlled phased-array antennas have a number of important benefits including size, weight, bandwidth, propagation loss, immunity to electromagnetic interference, remoting capability and simplified transmitting/receiving architectures. Functions, such as the distribution of RF signals, phase shifter control, true time-delay beam forming and processing of RF signals have been actively investigated over the past two decades[62–81].

In a phased-array radar, true time-delay (TTD) beam forming is needed to obtain wide instantaneous bandwidth and squint-free operation of the antenna array. A variety of approaches for this have been proposed and demonstrated. One of the earliest demonstrations of an optically steered phased-array antenna used a TTD network that incorporated fixed-length optical fibres as the delay elements and *N* sets of switchable fibre-optic delay lines with multiple sources to create an *N*-bit delay[64]. Later TTD networks incorporated high-dispersion optical fibres, where the dispersion property of the fibre-optic link was used to create variable delays for variable source wavelengths. An example is the single wavelength-tunable laser used in conjunction with dispersive fibre to create a fibre-optic prism[68], shown in Fig. 4.

Switching of the effective optical path length in optically controlled phased-array systems incorporating TTD has also been demonstrated using FBGs. Both non-chirped[69,74] and chirped[75,77] FBGs have been used as wavelength-selective time-delay elements. With the use of a chirped FBG, the time delay for the RF signal can be continuously varied by sweeping the wavelength of a tunable laser, and the required laser tuning range can be very narrow if a high-dispersion chirped FBG is used.

Other approaches have also been investigated for making use of optics in phased-array beam-forming networks including coherent detection techniques[65], and optical-signal-processing concepts[62,66,71,76]. In these latter approaches, which offer advantages for feeding large numbers of antenna elements, the beam-forming and multibeam operation of the phased-array antenna is controlled by an optical processor, which carries out the signal processing by means of Fourier optics. Another optical beam-forming scheme is based on a phase-control technique, where a spatial light modulator (SLM) is used to replace the microwave phase shifters in the phased array[63,66].

The area of optical phased arrays continues to be fertile for research and the main challenges for their practical use remain achieving robustness, system simplicity and low cost. A combination of TTD and phase control to reduce system cost has been recently reported[81], which has applications in phased-array systems with limited bandwidth. Progress has also been made in the integration of beam-former functions in InP (ref. 78) and silicon[79] technologies, which could substantially reduce the size and cost of the optical

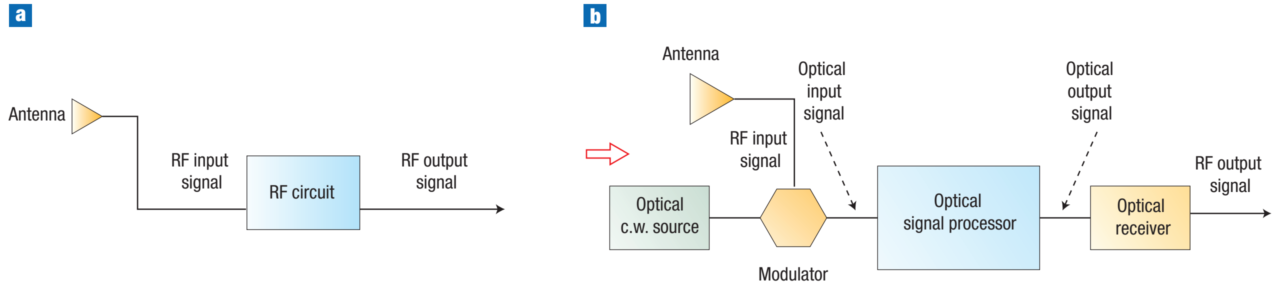

Figure 5 Schematics of RF signal processing. **a**, Traditional approach. **b**, Microwave photonic approach. (c.w. means continuous wave.) Reproduced with permission from ref. 85. Copyright (2005) IEEE and OSA.

beam-forming architecture. The use of WDM techniques to simplify the optical beam-forming architecture is also promising.

Microwave photonics techniques are also being used in radio-astronomy applications, such as the Square Kilometer Array (SKA)[82] and the Atacama Large Millimeter Array (ALMA) project[83]. Here, optics is being considered for the generation and distribution of high-frequency local oscillator signals to remotely located antennas and heterodyne receivers. The motivation is to make use of the low fibre transmission loss and avoid the need for costly local oscillator components that would otherwise have to be located at each of the many antennas in the array.

SIGNAL PROCESSING

Microwave photonics techniques offer unique features for the processing of microwave, millimetre-wave and RF signals. Three applications that have been extensively developed are microwave photonic filtering, microwave-signal analog-to-digital conversion and the generation of arbitrary waveforms.

FILTERS

The general concept behind microwave photonic filters is to replace the traditional approach towards RF signal processing, shown in Fig. 5a, by a new technique bringing unique flexibility and added value[82,84–87]. In the common approach towards microwave signal filtering, an RF signal originating from an RF source or coming from an antenna is fed to an RF circuit that performs the signal-processing tasks (usually at an intermediate frequency band after a down-conversion operation). In the case of the microwave photonic filtering approach, which is shown in Fig. 5b, the RF signal that now modulates an optical carrier is directly processed in the optical domain by a photonic filter based on fibre and integrated optical delay lines, devices and circuits.

The use of photonic components brings considerable advantages. For instance, microwave filters based on photonics can be made tunable and reconfigurable, a feature that is not possible with common microwave technologies. Progress in this field over the past 10 years has shown the feasibility of obtaining filters with tuning ranges from a few megahertz to over 20 GHz, dynamic ranges above 40 dB, *Q* factors above 1,000 in the 2 and 10 GHz bands, and the possibility of fast (below 1 ms) arbitrary transfer function reconfiguration by means of electronic control signals. Many of the above characteristics are simply unachievable with current microwave technology or may require costly extra down-conversion and analog-to-digital operations if digital signal processors (DSPs) are used.

Microwave photonic filtering technology is of interest in many applications. For example, in radio-over-fibre systems, it provides a means both for channel-rejection and channel-selection applications. In radio-astronomy applications[82] the signal transmission from several stations to a central site requires the removal of strong man-made interfering signals from the astronomy bands. The ability to reject these interfering RF signals directly in the optical domain is a unique characteristic of these photonic filters. Photonic filters for RF signals can also be of interest for applications where light weight is a prime concern; for example, analog notch filters are also needed to achieve co-channel interference suppression in digital satellite communications systems[88]. Finally in moving-target-identification radar systems[89,90], the filtering of clutter and noise directly in the optical domain greatly relaxes the system design.

Several approaches have been reported during the past few years. In most cases incoherent operation is preferred because it renders highly stable filters free from environmental fluctuations. Earlier work focused on filter structures, where optical delay lines were created by the use of fibre coils and single broadband sources were used to feed the filter. Work at Stanford University in the 1980s demonstrated the implementation of single-mode-fibre delay-line networks capable of synthesizing many sophisticated time- and frequency-domain filtering operations[91].

The advent of FBG technology in the middle of the 1990s opened the possibility of implementing reconfigurable and tunable filters using both uniform and linearly chirped gratings. Researchers at the University of Sydney pioneered this work[92–95]. The first continuously tunable notch filter was reported by Hunter and Minasian[92] in 1995, followed later by a bandpass configuration[93]. The notch filter configuration was based on a single tunable modulated laser source and two long, chirped gratings on separate ports of a coupler as tapping elements. Subsequent work by this group led to high-quality-factor ($Q = 938$) infinite-impulse-response (IIR) filters with wide and continuous tunable centre frequencies combining passive and active (that is, erbium-doped) photonic waveguides[94,95]. In parallel, researchers at the University of Aston reported more complex structures capable of providing transfer-function reconfiguration by means of tap apodization[96,97].

In 1999, researchers at the Universidad Politécnica de Valencia reported the first microwave photonic filter capable of simultaneous transfer-function reconfiguration and bandpass tunability[98]. Figure 6a shows the filter layout. The principal novelty arose from the use of different optical sources for the different filter taps. The modulated optical signal is then sent to a dispersive linearly chirped FBG, which performs a wavelength-to-time mapping producing equally spaced filter samples. By controlling the power delivered by the laser sources, it is possible to reconfigure the filter transfer function; by changing the wavelength separation of the optical carriers, the

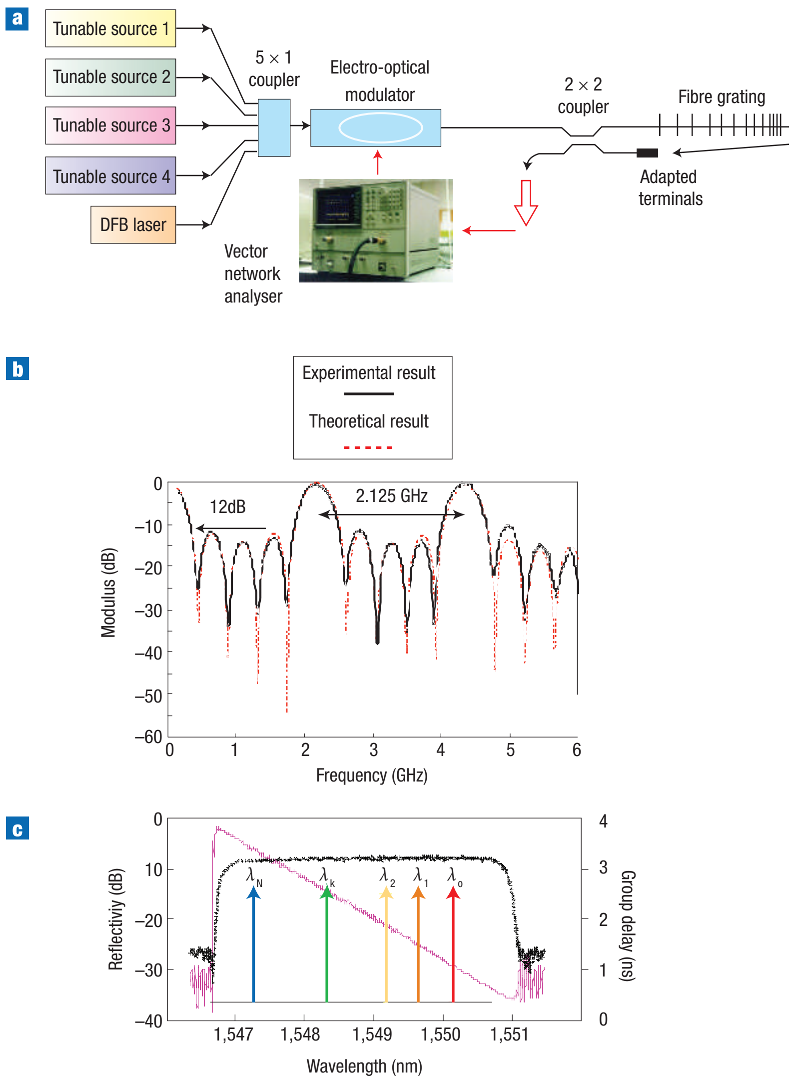

Figure 6 A reconfigurable and tunable microwave photonic filter using a laser source array and a dispersive linearly chirped FBG device. **a**, Schematic of the device. **b**, An example of a periodic MWP spectrum implemented by the filter. **c**, Dispersion characteristics of the linearly chirped FBG device used in the filter. The subscripts of the wavelength, λ, label the order in the wavelength spectrum. Reproduced with permission from ref. 98. Copyright (1999) IEEE.

filter bandpass can be tuned. Figure 6b shows a typical spectrum centred around 2.5 GHz. The tuning range can be easily extended over 40 GHz, and although the main-to-sidelobe ratio in this case was around 13 dB, researchers at ACREO, Sweden, have reported a filter with a ratio of over 40 dB in the 10 GHz region[99]. Lower-cost tunability using a spectrally sliced broadband source can be achieved by changing the dispersion characteristic of the FBG devices[100,101] or by switched delay lines[102].

Microwave photonic filters face several limitations; for incoherent filters, one of the main problems is that in principle only positive-valued samples can be produced (because optical intensity cannot be negative). Several different solutions have been proposed, including those based on differential detection[103], phase shift in wavelength conversion[104], and phase shift in dual input/output electro–optic modulators[105]. Furthermore, researchers at the Universidad de Navarra and the Universidad Politecnica de Valencia have recently demonstrated incoherent filters featuring complex-valued coefficients, by making use of the stimulated Brillouin scattering effect[106]. Another limitation of microwave photonic filters, especially in structures using single sources, is related to the effects of source coherence. Several schemes that provide the possibility of coherence-free operation have been proposed[107].

A third important limitation of microwave photonic filters is connected to the fact that the spectrum of microwave photonic filters is periodic. Single resonance filters have, however, been proposed and put into practice. Two technical approaches have been proposed, based respectively on the cascade of filters with a slightly different spectral period and the use of tuned (that is, frequency-selective) electro–optic modulators[108]. Two filters based on this last approach hold the current highest values of Q factors reported in the literature for transversal ($Q = 234$) and IIR ($Q = 3{,}300$) operation in the UMTS (Universal Mobile Telecommunications System, $f = 1.9$ GHz) band. High-Q transversal filters require a high number of signal taps, and for this purpose, coherent spatial architectures capable of providing a considerable number of spectral samples and yielding promising results are under current investigation[109].

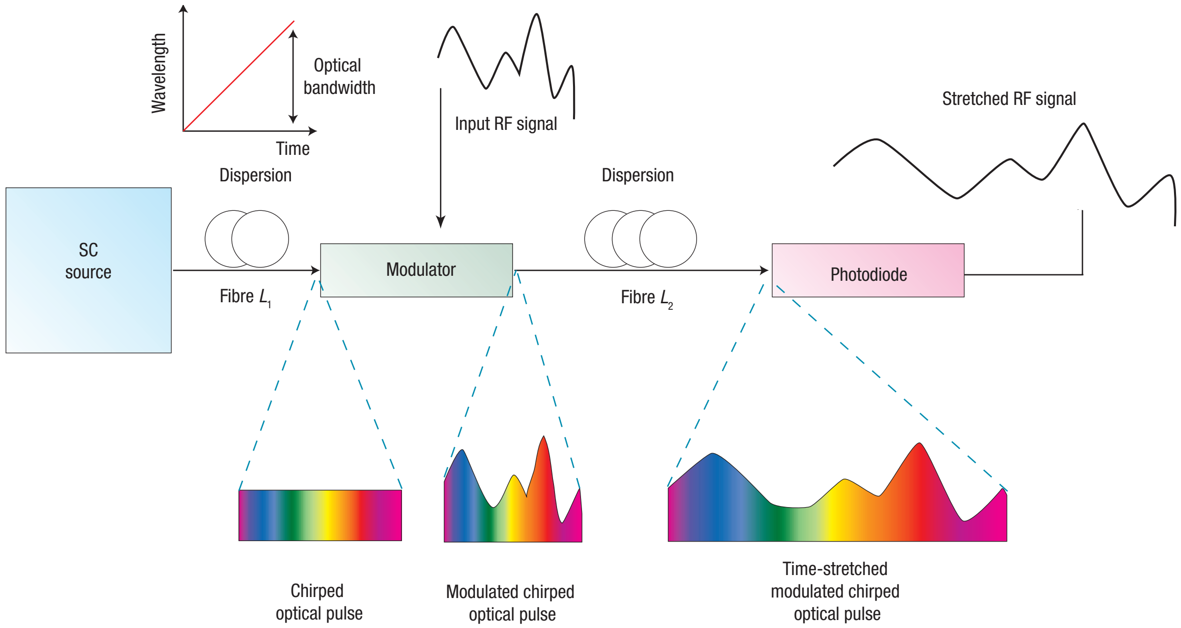

Figure 7 Block diagram of the photonic stretch processor. A linearly chirped optical pulse is obtained by dispersing an ultrashort, UWB pulse generated by a supercontinuum source at the first fibre link, length L_1. Time-to-wavelength mapping is achieved when the pulse is intensity-modulated by the electrical signal. The pulse is stretched in a second fibre link, length L_2. Reproduced with permission from ref. 117. Copyright (2003) IEEE and OSA

ANALOG-TO-DIGITAL CONVERTERS

A second field where MWP signal processing brings an important advantage is in UWB analog-to-digital converters[110–123]. In certain analog applications, such as high-performance broadband communication systems and radar, the use of digital signal processing provides superior performance and fast reconfigurability. The Achilles heel here is the fact that the analog-to-digital conversion (ADC) is the main bottleneck. Typical state-of-the-art electronic CMOS digitizers are limited in speed by several technology factors, including the jitter in the sampling clock, the settling time of the sample-and-hold circuit, the speed of the comparator and finally the mismatches in the transistor thresholds and passive component values. The limitations imposed by all these factors become more severe at higher frequencies. Although several of these limiting factors can be overcome using parallelism to implement time-interleaved ADC architectures, the current performance limit in the range of 100 gigasamples per second cannot be improved at the same rate as that required by the digital signal processors. For instance, their dynamic range and resolution are limited by mismatches between digitizers, with typical values for state-of-the-art electronic ADCs embodied by real-time digitizing oscilloscopes in the range of 20 gigasamples per second and a 4-GHz analog bandwidth. The performance of ADCs operating under arbitrary sources of noise and nonlinear distortion is characterized by the signal-to-noise and distortion ratio, SINAD, from which it is customary to define the effective number of bits (ENOB) of an ADC by ENOB = (SINAD – 1.76)/6.02, where SINAD is in decibels. For commercial state-of-the-art ADCs, the ENOB is approximately 4–5 bits, measured over the full bandwidth. An interesting option to circumvent these difficulties and extend the performance of electronic ADCs is to incorporate photonic techniques. Several approaches have been proposed[111–116] of which the photonic time-stretch (PTS) technique[116,117] has produced a record value of 480 gigasamples per second and 96 GHz intrinsic bandwidth[120].

Photonic time stretch improves the operation of an electronic ADC by slowing down the electrical signal by means of three photonic processing steps[117]: (1) time-to-wavelength transformation; (2) wavelength domain processing; and (3) wavelength-to-time mapping. Figure 7 shows a particular version of the above concept where a linearly chirped optical pulse is first generated by propagating broadband transform limited pulses (optical bandwidth Δf_{opt}) in a dispersive fibre (dispersion parameter β_2) of length L_1. The time duration of these pulses is the system time aperture $T_A = 2\pi|\beta_2|L_1\,\Delta f_{\mathrm{opt}}$. The electrical signal to be slowed down modulates the intensity of the chirped pulse in an electro–optic modulator and finally, the envelope of the pulse is stretched in a second fibre link (length L_2) before photodetection and digitization by a lower-speed electronic ADC. Overall, the modulated pulse is stretched in time by a factor $M = 1 + L_2/L_1$ and the effective sampling rate of the electronic digitizer f_s is increased to Mf_s. Another key important system parameter is the 3-dB electrical bandwidth Δf_{RF}. This depends on the modulation technique and in the case of double sideband modulation (DSB) it is given by $\Delta f_{\mathrm{RF}} = [M/(8\pi|\beta_2|L_2)]^{1/2}$.

From the operational point of view, the PTS system performance metric is given by the product of the time aperture and the RF bandwidth (TBP)[118]. If DSB modulation is used, the dispersion penalty limits the system performance to TBP values of around 100, because there is a trade-off between the time aperture and RF bandwidth. This limitation can be overcome, in principle, by using single sideband modulation (SSB)[119], and TBPs of several thousand can be achieved. But using SSB introduces several practical difficulties that must be taken into account. First of all, there is a residual phase distortion that must be corrected using an electronic equalizer. Second, SSB relies on the use of a microwave hybrid to provide quadrature outputs. The operation of the hybrid device is typically frequency-limited,

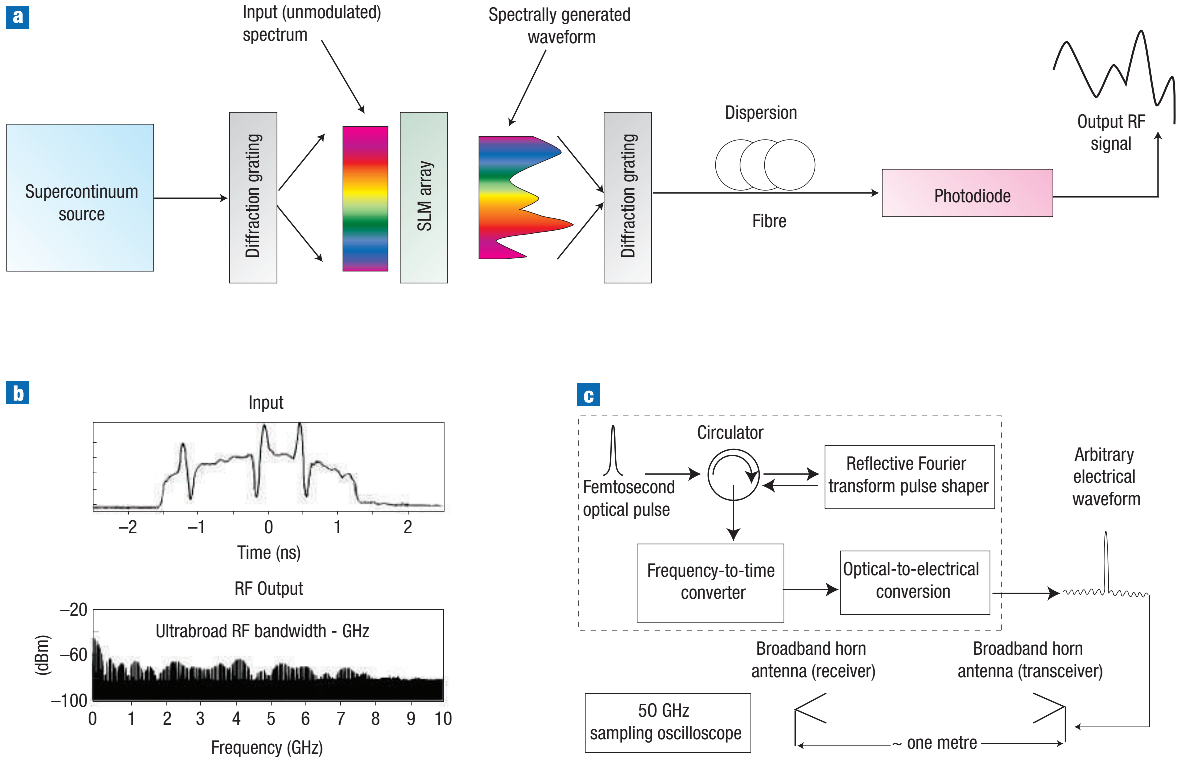

Figure 8 The photonic AWG comprising the spectral shaping of a supercontinuum source followed by a wavelength to time mapping[130,135]. **a**, Block diagram of the configuration. (Reproduced with permission from ref. 135. Copyright (2006) IEEE and OSA.) **b**, Generated ultra-broadband monocycle burst waveform[131]. (Reproduced with permission from ref. 131. Copyright (2005) IEEE.) **c**, Photonic AWG set-up used in ref. 134 to compensate for antenna dispersion effects in UWB communication system. (Reproduced with permission from ref. 134. Copyright (2006) IEEE.)

and thus SSB operation will also have a bandwidth limitation. Recently researchers at the University of California, Los Angeles proposed a new technique[120] to overcome the limitation imposed by dispersion, based not on SSB, but on the exploitation of the phase diversity that exists between the two outputs of a dual-output Mach–Zehnder modulator. Photonic-time-stretch ADCs have to solve several technical issues to offer continuous real-time operation, including calibration and channel matching, the impact of the noise from the optical source and the distortions in the dispersive fibre, which have been outlined by Valley[121] in a comprehensive review paper. Nevertheless, a 4.5-bit ENOB, 10 terasamples per second transient has recently been reported[122]. The Valley paper and the recent workshop held at the IEEE MTT-S International Microwave Symposium[123] provide further valuable information about this subject to the interested reader.

ARBITRARY WAVEFORM GENERATION

The generation of arbitrary microwave and RF waves is very useful in a variety of applications, including pulsed radar, UWB, optical and electronic tests and measurements and ground-penetrating radar[124–135]. Current electromagnetic arbitrary waveform generation (AWG) is band-limited to the range below 2 GHz. However, MWP signal-processing techniques can greatly improve the performance of these systems. A variety of photonic techniques have been developed during the past few years that can generate microwave waveforms in the gigahertz and multiple gigahertz region. For example, photonic AWG has been demonstrated by individually modulating the intensity and phase of the longitudinal modes of a mode-locked semiconductor laser[125]. Coherent pulse-shaping techniques based on direct space-to-time mapping[126–129] have been demonstrated for the production of both burst and continuous waveforms in the 30–50 GHz frequency range. Optical and microwave arbitrary waveforms have also been generated using fixed and programmable shaping of the spectrum of a supercontinuum followed by a wavelength-to-time mapping in a dispersive fibre link[130,131]. The operation of an equivalent scheme under incoherent operation[132] has also been proposed very recently, although no experimental verification has yet been provided. The potential of combined chromatic dispersion and nonlinear effects in optical fibres to generate complex microwave signals has also been investigated[133].

Of all the techniques described in the previous paragraphs, those based on the spectral shaping of a supercontinuum source followed by wavelength-to-time mapping have potential for the widest variety of applications. Figure 8a shows the first configuration proposed by Jalali and co-workers[130,135]. The principle of operation, which has some similarities to the time-stretching technique described above, is now explained. Supercontinuum generation in nonlinear fibres creates a broadband optical pulse and bandwidths in excess of 200 nm can be produced. The pulse spectrum is then bandpass-filtered to around 20 nm and spectrally dispersed by a diffraction grating. The different spectral components impinge on different pixels of a high-resolution SLM. Each pixel can apply precise levels of attenuation to its specific input spectral component. In this way the spectrum of the output light from the SLM can be carved.

The different spectral components are then focused onto a dispersive optical fibre link, which creates a one-to-one mapping between wavelength and time, converting the spectral modulation into a time-domain amplitude modulation. The length of the dispersive fibre link determines the temporal duration of the signal. On photodetection, the time variation of the electrical output signal is proportional to the optical intensity. The system performance is limited by the bandwidth of the photodiode, but with components available at present, bandwidths exceeding 60 GHz are achievable. The above system required a closed loop to generate an input control correction signal to the SLM to take into account the non-ideal feature of the dispersive fibre. This limitation was overcome in an open loop proposed by Andrew Weiner and colleagues[131]. Using this configuration, the researchers at Purdue University have demonstrated the synthesis of arbitrary waveforms in the UWB wireless communication spectral region and the ability to modulate the frequency of the RF carrier on a cycle-by-cycle basis, a feature that cannot be achieved with current electronic techniques. For instance, Fig. 8b shows a typical UWB signal generated, featuring monocycles of the order of 200 ps. This time resolution cannot be achieved with current electronic techniques.

Two salient features of the configuration in Fig. 8 have been recently demonstrated that outline the added value that MWP techniques bring to the synthesis of arbitrary microwave waveforms. First, the compensation of antenna dispersion effects[134] in impulsive UWB signals (3.1–10.6 GHz region) has been reported by extracting the RF spectral phase from a time-domain impulse-response measurement of the antenna and the subsequent programming of the matched signal in the SLM. Preliminary results have been reported for TEM antennas, but it is expected that it will be applicable to a variety of antennas operating in the UWB band. Figure 8c depicts the experimental configuration. Second, a photonic AWG has been successfully used to compensate for the gain ripple and phase distortion of RF cascade amplifiers required to boost the RF signal in broadband high-power waveform synthesis[135]. The results obtained set the path for obtaining high-power undistorted arbitrary microwave and millimetre-wave signals with voltages above 10 V.

FUTURE PROSPECTS AND CHALLENGES

Microwave photonics has succeeded in developing and demonstrating a wide range of devices, technologies and applications during the past three decades, some of which (especially those related to communications) have reached commercial realization. The key to accelerating the use of MWP techniques in real-world systems is to continue to improve the performance of the devices and links outlined in this review. In particular, the challenge is to improve their RF spectral region of operation, conversion efficiency and dynamic range, while at the same time reducing cost. In addition, the unique features of MWP devices need to be used to create emerging and future niche applications. Possible applications, such as optical packet switched networks and optical probing, are already being researched, while others, such as terahertz-wave generation and processing for non-invasive high resolution sensing and MWP-based quantum key distribution, are just around the corner.

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Competing financial interests

The authors declare that they have no competing financial interests.