Microwave Photonics

Alwyn J. Seeds, *Fellow, IEEE*, and Keith J. Williams, *Member, IEEE*

Invited Paper

***Abstract*—The low-loss wide bandwidth capability of opto-electronic systems makes them attractive for the transmission and processing of microwave signals, while the development of high-capacity optical communication systems has required the use of microwave techniques in optical transmitters and receivers. These two strands have led to the development of the research area of microwave photonics. This paper reviews the development status of microwave photonic devices, describes their systems applications, and suggests some likely areas for future development.**

***Index Terms*—Beam forming, microwave photonics, modulators, optical fiber, optical signal processing, phased array, photodetectors, semiconductor lasers.**

I. Introduction

THE DEFINITION of the research area of microwave photonics can be considered as falling into two parts: first, the study of opto-electronic devices and systems processing signals at microwave frequencies and, second, the use of opto-electronic devices and systems for signal handling in microwave systems. Initial work on microwave photonics started almost as soon as the laser was invented, so that a review of this area spans not only the entire period covered by this 40th Anniversary Special Issue but also virtually the entire period since that seminal invention. Digital optical-fiber systems now carry the bulk of terrestrial long-distance communications traffic, and fiber is increasingly being brought into the local access network. With many deployed long-distance systems having channel rates of 10 Gb/s and above, and the evolution of the ethernet standard to encompass a transmission rate of 10 Gb/s, most future optical communication systems will utilize microwave photonic techniques. The use of opto-electronics in microwave systems has now become a commercial reality in fiber-radio access networks, and there are emerging applications in phased-array antennas, electronic warfare, ultrafast noninvasive measurements, terahertz spectroscopy and imaging and radio astronomy.

Manuscript received May 23, 2006; revised September 28, 2006. The work at University College London in this area was supported in part by the U.K. Engineering and Physical Sciences Research Council, the European Union, the U.K. Ministry of Defence, the U.K.-Israel Science and Technology Research Fund, Marconi, the European Space Agency, the U.S. Army Research Office, and the U.S. Air Force Office of Scientific Research. The work at the Naval Research Laboratory was supported in part by the Office of Naval Research.

A. J. Seeds is with the Department of Electronic and Electrical Engineering, University College London, London, WC1E 7JE, U.K. (e-mail: a.seeds@ee.ucl.ac.uk).

K. J. Williams is with the Naval Research Laboratory, Washington, DC 20375 USA (e-mail: keith.williams@nrl.navy.mil).

Digital Object Identifier 10.1109/JLT.2006.885787

This paper will attempt to give some flavor of the history, current status, and future prospects of this interdisciplinary research field. Section II will describe some key examples of early work. Section III will consider technologies for the generation and detection of microwave rate modulated optical signals. Section IV will address the theory and technology of optical transmission links. Section V will describe applications to microwave systems. Finally, Section VI will consider future possibilities for the field.

II. Early Work

The key elements of microwave photonic systems are optical sources capable of fast modulation, suitable transmission media, and fast optical detectors or optically controlled microwave devices.

The development of the first lasers, including in 1960 both the pulsed ruby laser at Hughes Research Laboratories and the continuously operating helium neon laser at Bell Laboratories, can be said to have started the optical communications era. The important issue of how to modulate the output of these sources at high rates became the subject of intense activity. Important early microwave frequency electrooptic modulators include those of Blumenthal [1] and Johnson [2], while frequencies as high as 11 GHz were being achieved by the early 1970s [3].

Greater compactness was offered by the semiconductor laser, and with the development of double heterostructure devices capable of room-temperature continuous operation in 1970 [4], [5], this became the preferred source for optical communication. A further advantage of the semiconductor laser was its capability for direct modulation via the injected current, and microwave bandwidths were soon realized [6].

For transmission, early plans were based on free-space optics and gas lenses, but following predictions [7] and realization [8] of low-loss transmission in silica optical fiber this rapidly became the preferred transmission medium. Systems migrated from graded index multimode fiber operating with GaAs/AlGaAs lasers at a wavelength of 850 nm to take advantage of the lower loss and dispersion available with advanced single mode fiber (SMF) at 1300 nm and later 1500 nm. Early microwave analog-transmission links had very high electrical input to electrical output losses: frequently > 40 dB. Extensive component development efforts, described in more detail in Section III, eventually enabled links to be realized having net gain, without the use of electrical amplification.

For detection, fast depletion-style p-i-n and avalanche detectors were developed at an early stage [9], [10] and subsequently developed to give useful microwave bandwidth response [11], [12]. Direct optical control of microwave devices was also investigated, with early demonstrations of tuning of Gunn oscillators [13], tuning and power modulation of trapped plasma avalanche and transit time (TRAPATT) oscillators [14], and tuning of impact avalanche and transit time (IMPATT) oscillators [15], [16] by optical illumination. Injection locking of bipolar transistor [17] and IMPATT oscillators [18] to intensity-modulated optical signals was also achieved.

The potential of short pulse mode-locked lasers for measurements in microwave circuits and microwave signal generation also became a subject of considerable research interest [19]–[21] with a variety of pioneering demonstrations.

III. Microwave Photonic Device Technologies

A. Source Technologies

1) Directly Modulated Semiconductor Lasers: The simplicity of direct modulation of semiconductor lasers has proved attractive for many applications, and following early work on modulation characteristics [6], rapid progress has been made in reducing electrical parasitics of laser structures and optimizing laser parameters for high-speed operation. Modulation bandwidth is limited by the photon-electron resonance frequency ω_p above which the undamped detected electrical response falls as $1/\omega_{\mathrm{m}}^4$, where ω_{m} is the modulating frequency. ω_p can be approximated by

$$\omega_p = \sqrt{\frac{g_o S_o}{\tau_p(1+\varepsilon S_o)}} \qquad (1)$$

where g_o is the differential gain, S_o is the mean photon density, τ_p is the photon lifetime, and ε the gain compression factor. Faster response is therefore obtained by reducing the photon lifetime (short optical cavity, reduced facet reflectivity), increasing the differential gain (reduced dimensionality), and increasing the output power. The introduction of multiple-quantum-well active regions [22] led to considerable reductions in threshold current and an increase in differential gain by up to a factor of two relative to bulk devices, which from (1) leads to an increase in bandwidth of just over 40%. Fig. 1 shows the measured frequency response of an InGaAs-GaAs quantum-well laser emitting at a wavelength of 1.1 μm [23]. A -3 dB bandwidth exceeding 40 GHz is obtained. However, obtaining similar results at wavelengths convenient for optical-fiber transmission has proved difficult. An important limitation is gain compression, which has so far limited reliable 1.55 μm room-temperature operation lasers to bandwidths of about 30 GHz [24]–[26] despite much research effort.

2) External Modulators: The modulated component of the optical power output of an optical modulator can be written as

$$P_{\mathrm{om}} = k_{\mathrm{m}} V_i P_{\mathrm{op}} \qquad (2)$$

where k_{m} is the modulation sensitivity (V^{-1}), V_i is the modulating signal voltage, and P_{op} is the unmodulated optical input

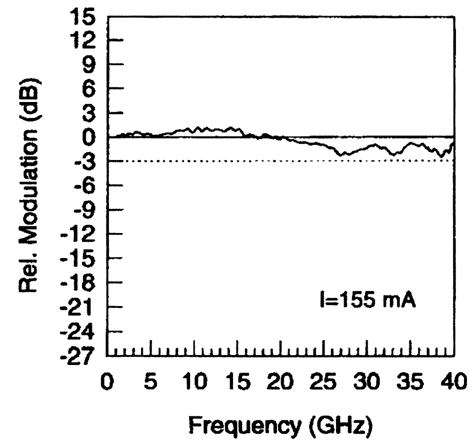

Fig. 1. Small-signal CW modulation response of 1.1 μm wavelength quantum-well laser [23].

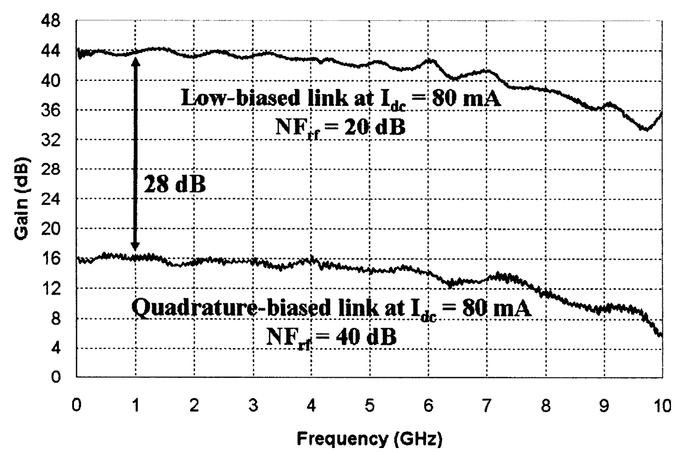

Fig. 2. Measured link gain against frequency for externally modulated quadrature-biased and low-biased (suppressed carrier) links [32].

power. It therefore follows that the amount of modulated optical power for a given modulating signal can be increased simply by increasing the optical input power, the limit being set by the power limits of the modulator. Use of this feature allowed the first demonstration of microwave photonic links displaying gain without the use of electrical amplification [27].

Interferometric modulators using lithium niobate and gallium arsenide technologies have been realized with -3 dB electrical bandwidths in excess of 40 GHz [28]–[30]. A 2 cm-long modulator of this design demonstrated a -3 dB electrical bandwidth of over 70 GHz with an extinction voltage V_π of 5.1 V [28]. Fiber-to-fiber insertion losses of intensity and phase modulators in this material system have reached 3 and 1.5 dB, respectively. Many recent advances in the lithium-niobate material system have made it possible to make high-power 20 GHz bandwidth modulators with a V_π of below 2 V [31] and optical power handling possibilities of over 1 W at 1550 nm wavelength. Use of low V_π modulators with high-current photodetectors has resulted [32] in link gains approaching 16 dB (4 GHz BW) and 12 dB (8 GHz BW) in a quadrature-biased link and over 40 dB gain in a suppressed carrier link, as shown in Fig. 2. Further modulator improvements will center around longer microwave-optical interaction lengths made possible with reductions in electrode loss [33], lower optical

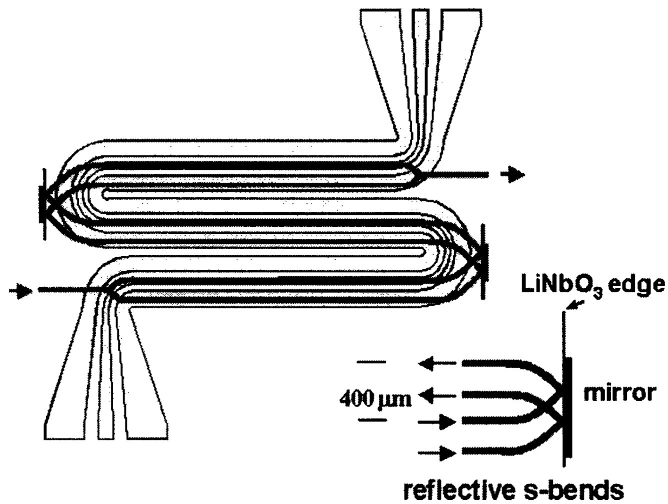

Fig. 3. Multipass lithium-niobate modulator design [33].

propagation loss, improved impedance matching, and better optical-microwave field overlap. This combined with 4 and 5 in wafer processing or multipass optical designs, as illustrated in Fig. 3 [33], allow for interaction lengths of over 10 cm with corresponding reductions in V_π.

Materials other than lithium niobate have also shown promise as external modulators. GaAs designs have achieved -3 dB electrical bandwidths of over 50 GHz and a V_π of 13 V for a 1 cm-long modulator [29]. The small size of the optical guides in GaAs leads to significant fiber-to-modulator-coupling losses so that the fiber-to-fiber loss for such modulators is on the order of 10 dB. Electro-optic polymer materials have also been the topic of recent research where r_{33} electrooptic coefficient values of 300 pm/V are being engineered. Modulator performance demonstrations have also been improving, with -3 dB electrical bandwidths exceeding 40 GHz with V_π values of 10 V and fiber-to-fiber insertion losses of 10 dB being obtained [34]. Operation at 110 GHz has also been demonstrated [35]. Significant problems of optical power handling, material stability, and high-temperature operation are still being addressed and need to be overcome for practical systems implementation.

Electro-absorption modulators operate by converting the incident light into photocurrent in their absorbing state. Waveguide modulators using the Franz–Keldysh effect in bulk semiconductor materials or the quantum confined Stark effect in quantum-well materials have been studied extensively. Bulk modulators at 1530 nm wavelength have achieved -3 dB electrical bandwidths of 50 GHz with 3.5 V drive for 20 dB extinction and fiber-to-fiber insertion loss of about 8 dB [36]. To obtain sufficiently low capacitance for such high-speed operation, the active section of the waveguide must be kept very short: 50 μm in this example, limiting the modulation sensitivity. Traveling-wave approaches can be used to improve this parameter [37], [38], and a 1300 nm-wavelength traveling-wave modulator with a -3 dB electrical bandwidth exceeding 5 to 40 GHz, small signal modulation sensitivity 0.65 V^{-1}, and fiber to fiber insertion loss of 11.3 dB has recently been demonstrated [38]. An attractive feature of electro-absorption modulators is that they can be integrated with semiconductor lasers to form compact optical sources capable of ultrafast modulation [39]. Recent advances in high-power semiconductor modulators have also been made with devices capable of handling over 100 mW of optical power [40], where careful quantum well and waveguide design was employed to prevent carrier bleaching at high power.

Coupling losses between optical fiber and semiconductor waveguide modulators can be reduced by moving to non-waveguide reflective modulator designs, where the light is incident perpendicular to the junction plane, as in the asymmetric Fabry–Pérot modulator (AFPM). In common with other electro-absorption modulators, these devices can also be used as detectors to create a duplex system, as described in Section V [107].

3) High-Power Continuous Wave (CW) Laser Sources: The widespread use of external modulators requires the use of a low-noise CW laser. The advantage that external modulation offers the link designer is the ability to design the CW laser separately from the modulation bandwidth or link linearity, which are determined by the modulator design. Since improvements in link loss, noise figure, and compression dynamic range rely on high detector photocurrents to obtain shot-noise-limited operation, research has focused on the design of high-power low-noise lasers. Examples of high-power semiconductor lasers include DFB [41], as well as low-gain designs [42], where power outputs have exceeded 150 mW and are nearing 1 W. Diode-pumped solid state lasers offer superior amplitude and phase-noise characteristics to those available from semiconductor designs due to the slow gain dynamics of the active rare earth ions. The most successful designs are based on the 1320 nm-wavelength transition in Nd : YAG [43] and the 1530 to 1550 nm wavelength-range transitions in Er : Glass. The 1550 nm-wavelength erbium laser is presently being pushed [44], [45] in both silica and phosphate glass hosts extensively because of the natural overlap with the mature erbium-doped fiber-amplifier (EDFA) technology.

4) Heterodyne Sources: Consider two monochromatic optical sources emitting at frequencies ω_1 and ω_2, where $|\omega_1 - \omega_2| \ll \omega_1, \omega_2$. If their optical fields are overlapped with common polarization and illuminate a photodetector of responsivity R, the resulting photocurrent is given by

$$i = R\left[P_1 + P_2 + 2\sqrt{P_1 P_2}\cos\left((\omega_1 - \omega_2)t + \phi_1 - \phi_2\right)\right] \tag{3}$$

where P_1 and P_2 are the powers, and ϕ_1 and ϕ_2 are the phases of the two sources incident on the detector. Note the term at the difference frequency between the two sources. Since lasers for long-haul optical communications typically emit at a frequency of order 200 THz, slight detuning of the sources enables frequencies limited only by the photodetector bandwidth to be generated.

Semiconductor lasers were readily applied to fast photodiode-frequency-response measurement [46]; however, the large free-running linewidth of non-line-narrowed semiconductor lasers (typically 1 to 50 MHz) coupled with the strong temperature and current dependence of their emission frequency (typically 10 GHz/K and 1 GHz/mA, respectively) required the application of special control techniques to obtain

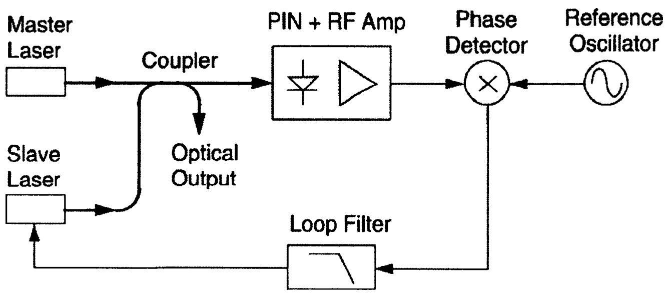

Fig. 4. OPLL microwave photonic transmitter [60].

a spectrally pure microwave heterodyne signal. Goldberg *et al.* [47] injection-locked two semiconductor slave lasers to different frequency-modulation sidebands of a semiconductor master laser, current modulated with a microwave source, thereby correlating the phase noise of the slave lasers. Heterodyne frequencies up to 35 GHz were obtained, with linewidths less than 10 Hz. More recently, injection locking to spectral lines from an optical comb generator has been used to generate frequencies up to 110 GHz [48], [49]. The main practical limitation on optical injection locking is that the locking range is small—typically a few hundred megahertz—so that the slave-laser temperatures must be controlled with milli-Kelvin precision, or lasers must be monolithically integrated to achieve thermal tracking [50].

An alternative technique for correlating the phase noise of the heterodyne sources is to use an optical phase-lock loop (OPLL) [51]–[60]. Fig. 4 shows the experimental arrangement required [60]. Part of the combined output from the two sources illuminates a photodetector, producing a signal at the difference frequency between the emissions from the sources. This signal is compared with a microwave reference frequency in a mixer and, following appropriate filtering, the output phase error signal is used to tune the slave laser so that the difference frequency exactly equals that of the reference. Although simple in principle and demonstrated for narrow linewidth gas lasers at an early stage in laser development [51], the practical realization of OPLLs is limited by the requirement that the loop delay should be small enough to ensure that phase fluctuations of the optical sources are accurately cancelled [52], [53]. The requirement for subnanosecond loop delays to lock non-line-narrowed semiconductor lasers led to much early work being carried out with narrow linewidth solid-state [54], [55] or external cavity semiconductor [56] lasers. Nevertheless, by careful microoptical design, first homodyne [57] and subsequently heterodyne [58], [59] loops were successfully realized using non-line-narrowed semiconductor lasers with linewidths of order 10 MHz, yielding reference source limited phase noise of better than -100 dBc/Hz at offsets of 10 kHz [60]. Fig. 5 shows a ruggedly packaged loop realized for use in phased-array antenna applications [60].

A method of overcoming the requirement for short loop propagation delay and hence microoptical construction when using non-line-narrowed semiconductor lasers is to combine injection locking with a phase-lock loop, forming an optical injection phase-lock loop (OIPLL) [61]. Here, control of close-to-carrier phase noise and laser frequency drift is through the phase-lock loop path, while wideband phase-noise suppression is achieved through the injection-locking path. Implementations of such loops with fiber pig-tailed components have demonstrated phase noise better than -92 dBc/Hz at 10 kHz offset from a 36 GHz generated signal using lasers of summed linewidth > 70 MHz [62].

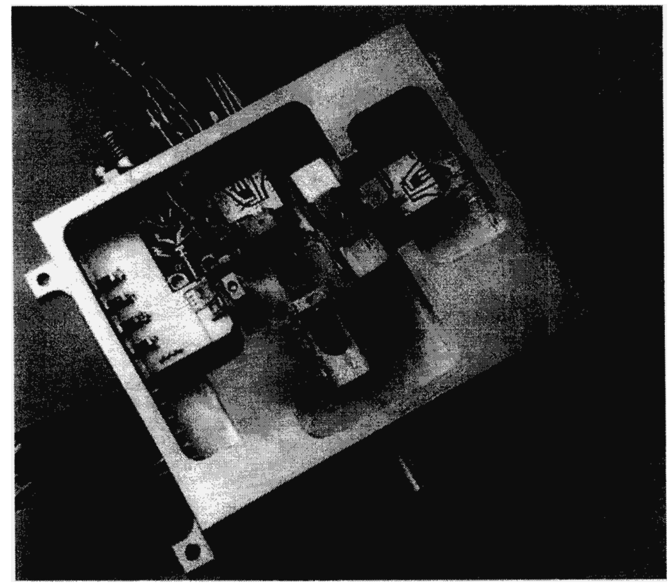

Fig. 5. Ruggedly packaged OPLL module [60].

A multimode single laser can also be used as a heterodyne signal source [63], [64]. For semiconductor lasers, microwave modulation of the injection current and, hence gain, provides a convenient method of locking the heterodyne frequency [64]. Tuning ranges of such sources are typically less than 10% of the heterodyne frequency.

5) Angle Modulated Sources: Although intensity modulation is used in by far the majority of analog links, because of its simplicity, angle modulated sources are used for long links, where stimulated Brillouin scattering restricts the performance. Phase modulation can be obtained using the electrooptic effect in waveguide modulators (see Section III-A2) or by the refractive index change induced by the Franz–Keldysh or quantum confined Stark effects [93]. Frequency modulation of semiconductor lasers by current or electrorefraction has also been used to create sources for such systems [92], [93].

B. Detection Technologies

1) Photodetectors: Metal–semiconductor–metal photodetectors have been used in a number of microwave photonic applications. The main attraction has been their compatibility for integration with field-effect-transistor (FET) devices in optically controlled microwave monolithic integrated circuits (MMICs). Bandwidths as high as 78 GHz have been reported [65] with an external quantum efficiency of 7.5% due to electrode blockage effects. Higher efficiencies are generally obtainable with depletion photodetectors. Avalanche photodiodes offer internal gain at the expense of higher operating voltages and temperature sensitivity. Using superlattice technology, 72% quantum efficiency and an avalanche gain > 10 have been obtained at a modulation frequency of 13 GHz and wavelength of 1.55 μm [66]. Since most analog links utilize high photocurrents to decrease noise figure and improve link loss, avalanche photodiodes are rarely used, except for certain niche applications.

The upper limit to depletion photodiode frequency response is set by transit time effects [67] and by the depletion capacitance of the diode unless traveling-wave techniques are implemented [68]. Optimization involves conflicting requirements since reducing the depletion width to increase the transit-time-limited frequency increases the depletion capacitance and can lead to incomplete absorption of light in geometries where light is incident normal to the junction plane. Loss of quantum efficiency can be compensated for in thin depletion-layer devices by adding doped absorbing layers [69] adjacent to the depletion region but with a general increase in some of their nonlinear characteristics. For high-speed operation waveguide, photodiodes with light incident parallel to the junction plane have been extensively studied [68] with multimode designs offering 110 GHz bandwidth with 50% quantum efficiency [70].

In high-dynamic-range microwave photonic systems, detector power handling and nonlinear effects are of great importance. The effect of the generated carriers on the electric field within the detector is an important limiting factor, which has been studied theoretically [71] and experimentally [72]. Traveling-wave configurations have been suggested to reduce the space charge density and obtain increased power handling capability [73], but surface illuminated designs, such as the partially depleted-absorber photodiode (PDA-PD), have yielded the highest currently handling performance to date [74]. These high-current handling designs make use of thin depletion regions combined with doped absorbers for increased efficiency. Other devices utilizing doped rather than fully depleted absorbers include the unitraveling-carrier photodiode (UTC-PD) [69], [75]. Thin depletion regions are key to obtaining high photocurrent for two reasons. First, since most photodiodes fail because of high thermal dissipation, the thin depletion region can attain higher electric fields for the same applied voltages, thus lowering Joule heating. Second, the space-charge effect is reduced because the space charge field is proportional to the number and separation of carriers within the depletion region, which are both reduced because of the short transit time. Fig. 6 shows a typical band diagram for a PDA structure [74]. Absorption occurs both in the doped and depleted regions. The electrons from the doped absorber are injected into the thin drift region. The electron transit time in the doped absorber can be enhanced with a small quasi-electric field from graded doping [74] or from majority hole current flow [76]. While doped absorber photodiode designs can offer operation to frequencies exceeding 300 GHz [75], excessive minority electron transit time can lead to additional small nonlinearities, including current-dependent bandwidth [74], nonlinear responsivity [77], and harmonic distortion [78]. PDA PDs have achieved record performance in terms of output radio frequency (RF) power, with over +24 dBm possible directly from the PD being reported at 2 GHz [79] with good power-conversion efficiency.

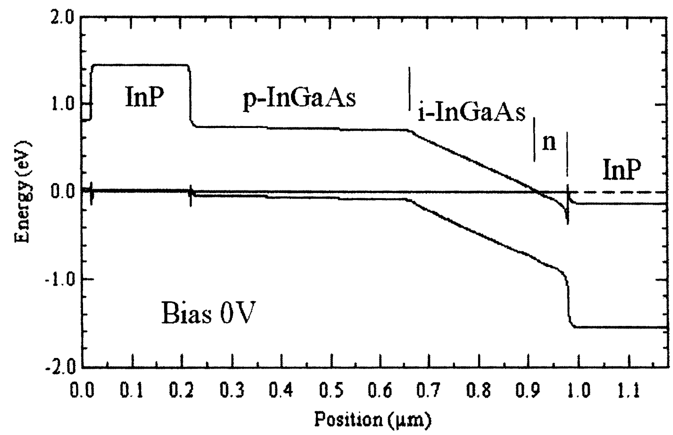

Fig. 6. Band diagram for surface illuminated designs PDA-PD [74].

Interfacing of photodiodes with subsequent amplifiers can be eased by monolithic integration, and impressive demonstrations of this have already been reported [80].

2) Optical Control of Microwave Devices: An alternative signal detection approach is to use the optical signal to control or introduce signals directly into microwave devices. This approach has several attractions. First, no extra electronic circuits are required to process the detected signals before application to the microwave device nor are any circuit parasitics, which may limit response speed, introduced. Second, optical control introduces an extra control port to the microwave device. Third, the optical-control signal is immune to most microwave electromagnetic disturbances. Indirect optical control, where the control signal is converted to an electrical signal by a photodetector before being applied to the microwave device, will not be considered here since it can be treated as conventional electrical control of the microwave device.

The basic process used in direct optical control of microwave devices is photogeneration of carriers within the device by the incident optical signal, usually through intrinsic absorption. In depletion regions, this produces a photocurrent and alters the built-in potential thus changing the device capacitance. In undepleted material, the photoconductive effect increases the conductivity of the semiconductor material.

Optical control of a wide range of microwave devices has been demonstrated [81]; some of the more important examples are described below together with some recent developments.

Amplifiers: The gain of microwave MESFETs and HEMTs depends strongly on the gate–source bias. It is possible to control the gain of amplifiers using these devices by illuminating the gate region and including an appropriate series resistor in the gate-bias circuit to produce a change in gate bias in response to the optically generated current [82]. Gain changes of up to 20 dB in MESFET amplifiers can be achieved using optical powers of a few microwatts. HEMT amplifiers exhibit an optical sensitivity that is typically between 7 and 10 times higher [83].

Oscillators: Three main forms of oscillator control are possible. In optical switching, a change in the intensity of the optical-control signal changes the oscillator output power. In optical tuning, the optical-control-signal intensity is also varied, but the intensities used are too small to produce significant oscillator output-power variation. Finally, in optical injection locking, the optical-control signal is intensity modulated at a frequency close to the free-running frequency of the oscillator ($k = 1$, fundamental locking), one of its harmonics (k integral, harmonic locking), or one of its subharmonics (k fractional, subharmonic locking). The modulated optical signal absorbed in the device active region gives rise to current flow at the modulation frequency in the device, leading to injection locking of the oscillator output frequency. These phenomena have been demonstrated for oscillators using avalanche diodes [84], MESFETs [85], and bipolar transistors [17]. The tuning and injection-locking ranges have generally been less than 1% of oscillator free-running frequency, owing to difficulty in coupling light into the active region of the device efficiently.

Optoelectronic mixers: In optically pumped operation, the signal to be converted in frequency is supplied electrically, and the local oscillator signal is an intensity-modulated optical source [86]. The converse arrangement in which an electrical local oscillator signal is used to downconvert an intensity-modulated optical signal has also been demonstrated [87]. Integrating the photodetection and mixing functions offers the attraction that electrical coupling between a separate detector and mixer with consequent matching and parasitic component problems is not required. Optoelectronic mixers have been realized using photoconductive devices [87], diodes [86], FETs [88], and bipolar transistors [89]. Much improved optical-control response has been demonstrated using heterostructure bipolar transistors in either normal incidence [90] or edge-illuminated [91] configurations.

IV. Analog Signal-Transmission Performance

Interest in the use of optical techniques for wideband signal transmission arises directly from the low transmission loss possible in optical fiber compared with electrical coaxial cable or waveguide. In order to avoid the modal noise problem characteristic of multimode fiber systems, SMF is used in most microwave photonic systems. For short-distance applications, loss and dispersion do not present a serious limitation, even at 850 nm wavelength, but for longer distance applications, such as cable-television distribution or antenna remoting, 1300–1600 nm wavelength-range operation is preferred. New fiber designs and dispersion compensation techniques make it possible to operate throughout this spectral window with good performance.

The output signal-to-noise ratio (SNR) of a microwave photonic link without embedded electrical amplification is given by [92]

$$\mathrm{SNR} = \frac{(mRP_{\mathrm{op}}G_{\mathrm{ot}})^2}{2B\left[N_{\mathrm{L}}(RP_{\mathrm{op}}G_{\mathrm{ot}})^2 + \overline{i_{\mathrm{na}}^2}/B + 2eRG_{\mathrm{ot}}P_{\mathrm{op}} + \frac{4kT}{R_{\mathrm{L}}}\right]} \quad (4)$$

where m is the modulation index, R is the photodiode responsivity, G_{ot} is the transmission path gain (fractional for unamplified fiber), B is the bandwidth in which the SNR is measured, N_{L} is the laser relative intensity noise (RIN), $\overline{i_{\mathrm{na}}^2}$ is the mean-squared output noise current due to optical-amplifier noise, e is the electronic charge, T is the absolute temperature, R_{L} is the detector load resistance, and k is Boltzmann's constant. Examination of (4) shows that the SNR can be increased by increasing the unmodulated optical power P_{op} until the laser RIN limit is reached. Utilization of low-RIN high-power lasers allows for shot-noise-limited SNR, which increases with increasing current. For long links (greater than a few kilometers), where fiber nonlinearity (Brillouin scattering) restricts the fiber launch power, high SNR can still be obtained by using fiber spans engineered for lower nonlinearity, optical angle modulation [93], or carrier suppression techniques [94].

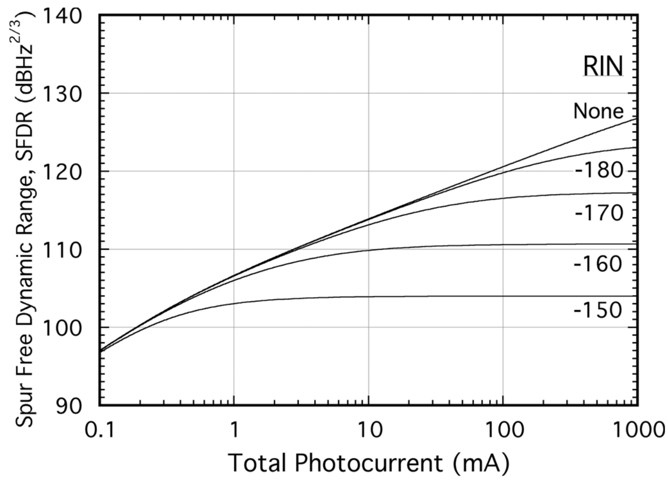

Fig. 7. SFDR of quadrature-biased MZM-based link as a function of photocurrent [98].

In analog links employing external Mach–Zehnder Modulators (MZM), the sinusoidal transfer function usually dictates the linearity of the link unless fiber [95], or photodetector [96] nonlinearities dominate. Biasing the modulator at quadrature yields the highest slope and the highest link gain or lowest loss. In addition to being the point of highest slope, operation at quadrature yields an odd transfer function thus minimizing the second-order-distortion output. Third-order distortion from the sinusoidal transfer function is a weak function of bias [97] and limits most practical links as it yields two-tone third-order distortions within typical signal bandwidths. Intermodulation distortion is usually quantified by the spurious free dynamic range (SFDR), which is defined as the largest input SNR signal possible without observation of measurable distortion products above the noise floor. For quadrature-biased MZMs, the SFDR is only a function of photocurrent [98] and laser RIN, as shown in Fig. 7, unless the modulator sensitivity becomes so high that input thermal noise appears at the output of the link. SFDR values of greater than 120 dB $\cdot$ Hz$^{2/3}$ [96] have been achieved for a 100 mA balanced detection link over multi-octave bandwidths. Higher multioctave dynamic-range links will likely focus on techniques to linearize the MZM transfer function [99]–[101], feedback or feed forward compensation, or coherent frequency or phase (angle) modulation.

The development of optical amplifiers has enabled "transparent" optical networks to be realized, in which signals of near arbitrary format can be distributed with small degradation due to noise and amplifier nonlinearity. The most important technologies for amplifiers are the traveling-wave semiconductor optical amplifier (SOA) [102] and the EDFA [103]. The EDFA is pumped using a semiconductor laser and has the advantage that it can be spliced directly into a fiber system, avoiding significant coupling losses. Since the fluorescence lifetime of erbium is long (> 10 ms), low distortion performance can be maintained for modulation frequencies down to the megahertz region, whereas SOAs generally show substantial distortion below a few hundred megahertz since typical carrier lifetimes are of the order of a nanosecond.

The choice between SOAs and EDFAs for microwave opto-electronic applications depends on the systems context. SOAs can be integrated into opto-electronic integrated circuits, whereas EDFAs interface naturally with fiber systems. SOAs offer greater power-added efficiency, which is an important requirement for space applications, whereas EDFAs offer lower added noise and lower minimum modulation frequency. It therefore seems likely that both types will find applications.

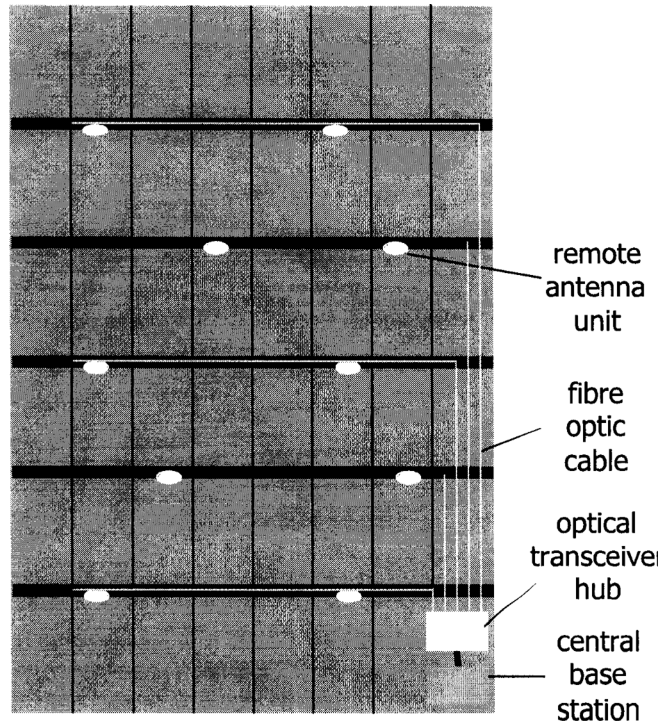

Fig. 8. In-building fiber distributed antenna system.

V. Applications

A. Wireless-Over-Fiber Systems

The principal attraction of wireless-over-fiber technology is that it centralizes most of the transceiver functionality by transmitting the wireless signals in their modulated format over fiber and reduces the fielded access points to antennas with associated amplifiers and frequency converters. Standards-independent and multiservice operation is facilitated.

At frequencies used for existing cellular systems (900 MHz and 1.8 GHz for GSM, 2 GHz for UMTS), semiconductor lasers, directly modulated with the data modulated RF signals, SMF, and wide bandwidth photodiodes are preferred for wireless-over-fiber systems. Fig. 8 shows a typical system layout. Wireless base stations are located in a central communications room and their outputs/inputs fed through RF multiplexers to lasers/photodiodes contained within the optical transceiver hub. The modulated optical signals are linked to/from the remote antenna units (AUs) in the building using single-mode optical fiber. A major cost saving is becoming available in such links with the development of high-linearity uncooled laser diodes [104].

Strong growth in the use of IEEE 802.11 a/b/g wireless local area networks (WLAN) has led to the development of systems for the simultaneous transmission of multiple WLAN channels over a single wireless-over-fiber link [105], showing the wide dynamic-range capabilities available with modern directly modulated lasers.

For in-building applications, there has been considerable interest in the passive picocell concept [106], in which the base station uses a combined detector/optical modulator, which is directly coupled to the antenna, so that no electrical amplification or other processing is required. Typically, a waveguide electro-absorption modulator is used as the detector/modulator. However, this leads to system penalties due to the polarization dependence of the modulator and the high optical insertion loss. A more recent approach uses a normal incidence AFPM to give polarization independence and a low optical insertion loss by direct coupling to single-mode optical fiber [107].

Multimode fiber, although forming by far the majority of the in-building installed fiber base, has seen restricted use for wireless-over-fiber applications, since its small bandwidth $\cdot$ distance product (typically < 500 MHz $\cdot$ km) requires signal transmission at intermediate frequency (IF) with up/down conversion at each AU [108]. Above the multimode fiber cutoff frequency, the transmission response is fairly uniform, but at a lower level, and it has been shown to be possible to use this frequency range for wireless-over-fiber transmission without down/up conversion [109].

To cater for growth in broadband, wireless-access application spectrum has been made available in the 28, 40, and 60 GHz bands. Here, single sideband techniques are preferred to overcome dispersion limits on propagation in standard SMF. At higher frequencies, where direct modulation or external modulators are not available, a wide variety of techniques have been investigated [110]–[116] to provide broadband wireless-over-fiber access while minimizing the fiber dispersion penalties resulting from the high carrier frequency. These include dispersion compensation [112], frequency multiplying modulators with sideband filtering for modulation [113], optical single sideband modulators [114], synchronization of a mode-locked laser to a subharmonic optical clock, and optical injection locking of two slave lasers to spectral lines from a directly modulated master laser, as described in Section III-A4 [116]. Of these methods, dispersion compensation requires adjustment if the fiber span length is changed and the modulator approaches suffer substantial optical loss, whereas the power

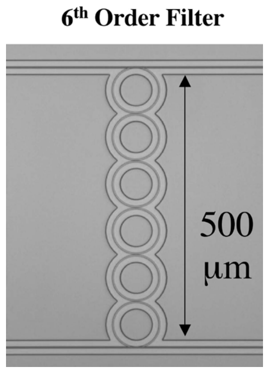

Fig. 9. Sixth-order microring-resonator filter [125].

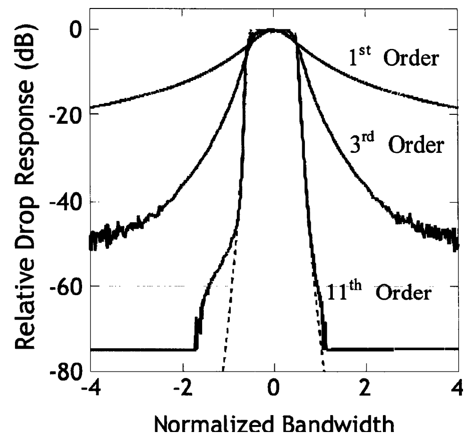

Fig. 10. Transmission characteristics of microring-resonator filter as a function of order [125]. Bandwidth normalized to the −3 dB filter bandwidth.

output at the required modulation frequency from mode-locked lasers is usually small so that optical amplifiers are required, increasing the system cost. Injection-locking approaches offer high launch power, reducing the need for optical amplifiers, but require milli-Kelvin temperature control of the slave lasers for reliable operation. Use of the OIPLL technique described in Section III-A4 overcomes these limitations [117].

The cable television industry is also using broadband fiber technology for distribution of both analog and digital signals [118]. Each modulated channel is mixed with a subcarrier in the electrical domain to form a composite signal, which is used to modulate the optical source. Linearity requirements in such systems are stringent [119].

B. Signal Processing

Optical-fiber delay lines offer longer delays for microwave bandwidth signals than competing technologies, such as bulk acoustic wave devices. Deborgies *et al.* [120] report a 100 μs optical-fiber delay line with a directly modulated semiconductor laser source for use up to 8 GHz. SNR exceeds 127 dB·Hz up to 4 GHz, falling to 115 dB·Hz at 8 GHz. Higher figures would be achievable using an externally modulated source. However, the existing system exceeded the performance of bulk acoustic wave technology for all frequencies greater than 1 GHz. Such delay lines are useful in radar target simulators [121].

Optical filters with microwave bandwidths using fiber delay lines have been extensively investigated [122], [123], and the development of doped fiber amplifiers, fiber Bragg gratings, planar glass waveguides [124], high-index glass waveguides [125], and microring resonators [125], [126] has considerably widened the possibilities for filter synthesis. Fig. 9 [126] shows a six-pole microring-resonator technology that is capable of demonstrating exceptional higher order filtering functions. Excellent insertion loss, flat-top shape, high skirt steepness, and rejection for filters made with these resonators in high-index glass waveguides are shown in Fig. 10, and performance comparable to microwave filter technology can be obtained. Future work will likely be focused on narrowing filter bandwidth and implementing tunable designs.

Multioctave bandwidth signal processing receiver design with improved rejection of intermodulation and spurious responses has been demonstrated by using optical modulators as photonic mixers [127]. Here, the optical input to the modulator is intensity modulated by the local oscillator signal, and the signal is applied to the electrical input. The configuration also has the advantage that there is no local oscillator radiation from the signal port.

Signal processing has also been applied to free-space optical systems. Significant gains in detection sensitivity have been demonstrated by applying coherent microwave detection techniques to LIDAR for detection of undersea objects [128].

C. Downconverting Links

Many RF systems incorporate up- and down-conversions for processing signals. Many of these systems utilize fixed IFs followed by further narrowband analog processing, such as correlation or direction finding, or by analog-to-digital conversion with subsequent digital signal processing. Up- and down-conversions within an optical link have been accomplished by a variety of techniques. Some of the most promising of these utilize multiple external modulators [129] to implement the required frequency conversions, where one modulator is used to impress a local oscillator and the second modulator impresses the RF signal, with the IF recovered to the electrical domain at the output of the photodetector. The advantages of optical mixing include remoting of the local oscillator from the RF signal location as well as excellent RF-LO isolation.

Improvements needed in downconverting links include designs to provide image rejection, improve multisimultaneous-signal performance, and the development of techniques to increase the dynamic range. Some efforts to implement image reject downconversion [130] or multiple simultaneous downconversion [131] of many RF channels have been demonstrated, but further work is needed in this area.

D. Antenna Beam Forming

In a phased-array antenna, the beam is formed by adjusting the phase relationship between a number of radiating elements. Advances in MMIC make it possible to use active elements at acceptable cost. Much of the expense then lies in the signal-distribution scheme required to obtain the necessary phase relationship between elements. Traditional microwave power

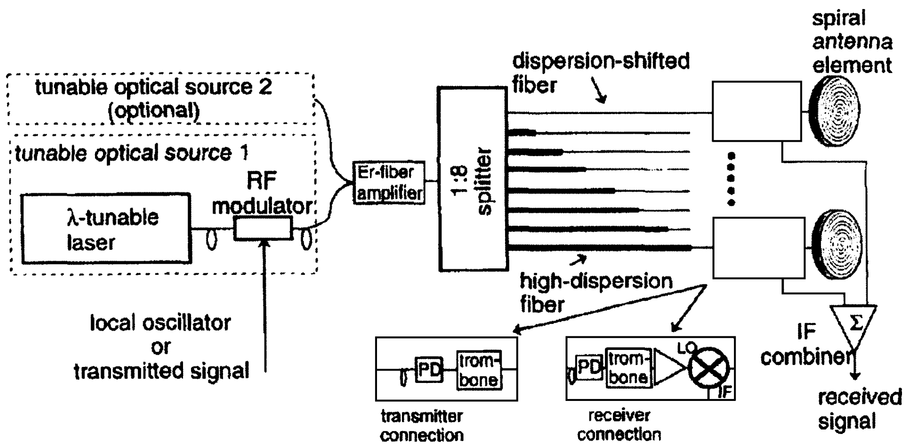

Fig. 11. True time-delay beam former using dispersive fiber [139].

splitters and transmission systems are cumbersome and lossy, particularly at millimeter-wave frequencies. There has thus been interest in optical-fiber techniques for both signal transmission [132] and, more recently, for beam forming [133].

Technologies for optical beam forming are shaped by the lack of fast (< 1 ns) low-loss (< 1 dB) optical switches and application-dependent requirements for instantaneous bandwidth. For most communications applications, very wide ($> 20\%$ of center frequency) bandwidths are not required, and antenna apertures are modest. Coherent beam forming, using the heterodyne approach of Section III-A4, with phase shift applied to one source only, then becomes attractive [134]. Significant progress has been made in integrating the beam former functions in GaAs and $LiNbO_3$ [134] in silicon [135] and in InP [136] technologies.

For applications such as wideband, large aperture radar, where true time delay beam forming is required, switching of the effective optical path length is required. This has been achieved using multiple sources and detectors [137] and two-dimensional free-space optics [138]. Fig. 11 shows a method using a tunable laser and an array of fibers having different dispersion values [139]. As the laser is tuned, the differential delay between fiber paths changes, thus steering the beam. Fiber Bragg gratings can be used to perform the same function [140].

The use of complex digital signal processing in radar has led to a desire to convert signals at the array face into digital form and carry out all subsequent processing digitally. Optical techniques are being applied to analog-to-digital converters to achieve the wide bandwidth and wide dynamic range required, with targets of > 18 GHz at > 8 bit resolution [141]–[143]. Representative results achieved so far include 8 bit SFDR at 10 Gsa/s [143].

E. Other Applications

With the availability of submillimeter-wave bandwidth photodetectors capable of milliwatt-level output power, there are attractive possibilities for optical local oscillator generation and distribution in systems such as radio telescope arrays or for timekeeping. For radio astronomy, phase noise and stability require careful attention [144]. Signals at frequencies > 1 THz locked to a microwave reference can be generated using optical comb generators [145]. Combining optical comb generation with injection-locked comb line selection has allowed optical synthesis of signals from 10 to over 900 GHz to be demonstrated [146].

At lower frequencies, the best RF oscillators that have been demonstrated utilize Sapphire resonant cavities for high Q. High Q has also been achieved with opto-electronic oscillators where the long delay and low loss possible in optical fiber can also be used to produce low phase-noise microwave oscillators [147]–[149]. The most active area of very high-stability opto-microwave generation utilizes self-referenced mode-locked femtosecond lasers (MLFL) [150]. In these systems, an MLFL with spectral lines spanning an octave can lock their envelope offset frequency by frequency doubling the long wavelength spectral lines and mixing with the short wavelength portion of the spectrum to extract and subsequently lock the envelope offset frequency. Locking the envelope offset frequency to dc or to a low-frequency low-noise reference effectively locks one of the lower frequencies of the comb line. Then, a longer wavelength spectral line of the MLFL can be locked to an atomic reference. With two widely spaced lines of the laser locked, the stability of the atom's transition and low-frequency reference can be transferred to any other spectral component of the MLFL as all lines of the laser are well defined by the stability of the two references. Such systems offer the promise of pushing well beyond the stability of conventional RF oscillators such as those used in the global positioning system. Recent work [151] has demonstrated record stability in terms of phase noise, especially close to the carrier, with further improvements being projected. The single-sideband phase-noise characteristic obtained from a Ti-Sapphire system is shown in Fig. 12, where impressive phase noise in the optical domain was obtained. However, transferring the optical signal to the electrical domain (where it can be used for timekeeping) via photodetection results in degraded phase noise. Improved photodetectors are thus needed to realize the full potential of MLFLs for high-stability RF signal generation.

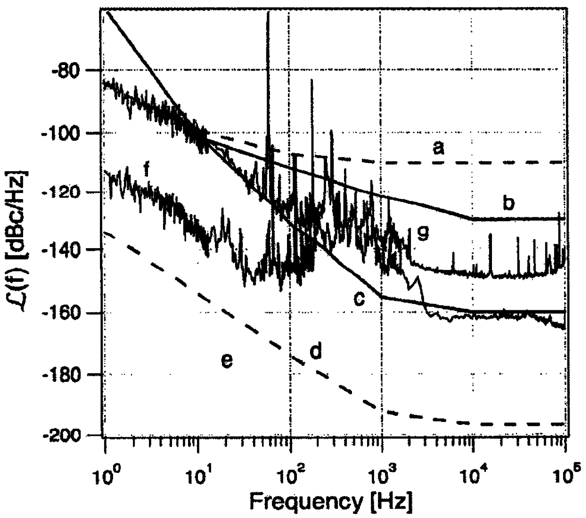

Fig. 12. Comparison of phase-noise spectrum at 1 GHz between (a) low-noise quartz oscillator, (b) low-noise RF/microwave synthesizer, (c) sapphire loaded cavity oscillator, (d) projected for Ca optical standard, (e) projected for visible laser that serves as a reference for Hg^+ optical standard, (f) optical pulse train output of femtosecond laser synthesizer, and (g) microwave electronic output of femtosecond laser synthesizer [150].

Opto-electronic probing of microwave and ultrafast digital integrated circuits offers unique low-invasive characterization at millimeter-wave frequencies and above [152], [153] and has now been developed to a state where ease of use is comparable to conventional network analysis.

VI. Conclusion—Future Prospects

Microwave photonics has demonstrated a remarkable range of capabilities since the inception of the field. Directly modulated sources, external modulators, and detectors, with bandwidths extending well into the millimeter-wave region, are now commercially available. The use of external modulators with high-power low-intensity noise sources enables optical links with excellent noise performance to be realized. Optical-amplifier technology enables broadband networks with well-controlled noise performance to be constructed and plays an important part in distribution networks for cable television. Wireless over fiber for cellular access has become a significant commercial market. With the drive to offer broadband wireless access, it is very likely that the market share of wireless-over-fiber access systems will grow further.

With the majority of fixed communication now being by optical fiber and per-channel data rates expected to rise through 40 Gb/s, the need for microwave photonics technology in this large market is assured.

For optical signal processing, growth in applications is dependent on the achievement of wide dynamic range. Novel architectures involving optically controlled devices are possible [154], and these are becoming more attractive as the optical response of microwave devices has been improved. With the flexibility of digital signal processing, a key technology is greatly improved analog-to-digital converters, and more work is required on extremely low jitter optical pulse sources if the systems targets are to be met.

Optical beam forming for phased-array antennas has shown useful capabilities and is likely to see application in communications antennas. The strong interest in digital processing for radar may mean that substantial development is required in optical sampling technology before wide-scale application takes place.

Recently, demonstrated capabilities for optical generation of millimeter-wave and submillimeter-wave (terahertz) signals are likely to play a significant part in increasing utilization of this part of the frequency spectrum.

The unique low-invasiveness advantages of opto-electronic probing of ultrafast circuits suggest that this will be an area of major growth as short pulse optical sources continue to reduce in cost and become simpler to operate. Advances in coherent optical signal generation and processing technology suggest that it will play an increasing part in optical-signal-processing schemes.

In conclusion, microwave photonics has demonstrated a remarkable range of capabilities since the inception of the field. Those related to signal transmission have become commercially important. Several other areas have achieved niche exploitation. With continued investment in the underlying technology, driven by the requirements of high-capacity optical communications systems, many more applications will also come to fruition.

Acknowledgment

Owing to space restrictions, it has only been possible to reference a few examples from the large body of excellent published work consulted in preparing this paper. The authors would therefore like to thank their colleagues in academe and industry for their many contributions to advancing the field of microwave photonics whether their work has been specifically cited here or not.

References

[1] R. H. Blumenthal, "Design of a microwave frequency light modulator," *Proc. IRE*, vol. 50, no. 4, pp. 452–456, 1962.

[2] K. M. Johnson, "Microwave light modulation by the Pockel effect," *Microw. J.*, vol. 7, no. 1, pp. 51–56, 1964.

[3] R. D. Standley and G. D. Mandeville, "Performance of an 11 GHz optical modulator using $LiTaO_3$," *Appl. Opt.*, vol. 10, no. 5, pp. 1022–1023, May 1971.

[4] I. Hayashi, M. B. Panish, P. W. Foy, and S. Sumski, "Junction lasers which operate continuously at room temperature," *Appl. Phys. Lett.*, vol. 17, no. 3, pp. 109–111, Aug. 1970.

[5] Z. I. Alferov, V. M. Andreev, D. Z. Garbuzov, Y. V. Zhilyaev, E. P. Morozov, E. L. Portnoi, and V. G. Triofim, "Investigation of the influence of the AlAs-GaAs heterostructure parameters on the laser threshold current and the realisation of continuous emission at room temperature," *Fiz. Tekh. Poluprovodn.*, vol. 4, no. 9, p. 1826, 1970.

[6] T. Ikegami and Y. Suematsu, "Resonance-like characteristics of the direct modulation of a junction laser," *Proc. IEEE*, vol. 55, no. 1, pp. 122–123, Jan. 1967.

[7] K. C. Kao and G. A. Hockham, "Dielectric-fiber surface waveguides for optical frequencies," *Proc. Inst. Electr. Eng.*, vol. 133, no. 3, pp. 1151–1158, Jul. 1966.

[8] F. P. Kapron, D. B. Keck, and R. D. Maurer, "Radiation losses in glass optical waveguides," *Appl. Phys. Lett.*, vol. 17, no. 10, pp. 423–425, Nov. 1970.

[9] R. P. Rietz, "High speed semiconductor photodiodes," *Rev. Sci. Instrum.*, vol. 33, no. 9, pp. 994–999, Sep. 1962.

[10] K. M. Johnston, "High speed photodiode signal enhancement at avalanche breakdown voltage," *IEEE Trans. Electron Devices,* vol. ED-12, no. 2, pp. 55–63, Feb. 1965.

[11] J. E. Bowers, C. A. Burrus, and R. J. McCoy, "InGaAs PIN photodetectors with modulation response to millimeter wavelengths," *Electron. Lett.*, vol. 21, no. 18, pp. 812–814, 1985.

[12] K. Berchtold, O. Krumpholz, and J. Suri, "Avalanche photodiodes with a gain-bandwidth product of more than 200 GHz," *Appl. Phys. Lett.*, vol. 26, no. 10, pp. 585–587, May 1975.

[13] P. Guetin, "Interaction between a light beam and a Gunn oscillator near the fundamental edge of GaAs," *J. Appl. Phys.*, vol. 40, no. 10, pp. 4114–4122, Sep. 1969.

[14] R. A. Kiehl, "Behaviour and dynamics of optically controlled TRAPATT oscillators," *IEEE Trans. Electron Devices*, vol. ED-25, no. 6, pp. 703–710, Jun. 1978.

[15] H. P. Vyas, R. J. Gutmann, and J. M. Borrego, "Leakage current enhancement in IMPATT oscillators by photo-excitation," *Electron. Lett.*, vol. 13, no. 7, pp. 189–190, 1977.

[16] H. W. Yen, M. K. Barnoski, R. G. Hunsperger, and R. T. Melville, "Switching of GaAs IMPATT diode oscillator by optical illumination," *Appl. Phys. Lett.*, vol. 31, no. 2, pp. 120–122, Jul. 1977.

[17] H. W. Yen and M. K. Barnoski, "Optical injection locking and switching of transistor oscillators," *Appl. Phys. Lett.*, vol. 32, no. 3, pp. 182–184, Feb. 1978.

[18] A. J. Seeds and J. R. Forrest, "Initial observations of optical injection locking of an X-Band IMPATT oscillator," *Electron. Lett.*, vol. 14, no. 25, pp. 829–830, 1978.

[19] S. Jayaraman and C. H. Lee, "Observation of two-photon conductivity in GaAs with nanosecond and picosecond light pulse," *Appl. Phys. Lett.*, vol. 20, no. 10, pp. 392–395, May 1972.

[20] P. R. Smith, D. H. Auston, and W. M. Augustyniak, "Measurement of GaAs field-effect transistor electronic impulse response by picosecond optical electronics," *Appl. Phys. Lett.*, vol. 39, no. 9, pp. 739–741, Nov. 1981.

[21] M. S. Heutmaker, T. B. Cook, B. Bosacchi, J. M. Wiesenfeld, and R. S. Tucker, "Electro-optic sampling of a packaged high speed GaAs integrated circuit," *IEEE J. Quantum Electron.*, vol. 24, no. 2, pp. 226–233, Feb. 1988.

[22] J. P. van der Ziel, R. Dingle, R. C. Miller, W. Wiegman, and W. A. Nordland, Jr., "Laser oscillation from quantum states in very thin $GaAs - Al_{0.2}Ga_{0.8}As$ multilayer structures," *Appl. Phys. Lett.*, vol. 26, no. 8, pp. 463–465, Apr. 1975.

[23] S. Weissner, E. C. Larkins, K. Czotscher, W. Benz, J. Daleiden, I. Esquivias, J. Fleissner, J. D. Ralston, B. Romero, R. E. Sah, A. Schonfelder, and J. Rosenweig, "Damping limited modulation bandwidths up to 40 GHz in undoped short cavity $In_{0.35}Ga_{0.65}As - GaAs$ multiple quantum well laser," *IEEE Photon. Technol. Lett.*, vol. 8, no. 5, pp. 608–610, May 1996.

[24] P. A. Morton, T. Tanbun-Ek, R. A. Logan, N. Chand, K. Wecht, A. M. Sergent, and P. F. Sciortino, Jr., "Packaged 1.55 μm DFB laser with 25 GHz modulation bandwidth," *Electron. Lett.*, vol. 30, no. 24, pp. 2044–2046, Nov. 1994.

[25] Y. Matsui, H. Murai, S. Arahira, S. Kutsuzawa, and Y. Ogawa, "30 GHz bandwidth 1.55 μm strain-compensated InGaAlAs-InGaAsP MQW laser," *IEEE Photon. Technol. Lett.*, vol. 9, no. 1, pp. 25–27, Jan. 1997.

[26] O. Kjebon, R. Schatz, S. Lourdudoss, S. Nilsson, B. Stalnacke, and L. Backbom, "30 GHz direct modulation bandwidth in detuned loaded InGaAsP DBR lasers at 1.55 μm wavelength," *Electron. Lett.*, vol. 33, no. 6, pp. 488–489, Mar. 1997.

[27] C. H. Cox, III, G. E. Betts, and L. M. Johnson, "An analytic and experimental comparison of direct and external modulation in analog fiber-optic links," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-38, no. 5, pp. 501–509, May 1990.

[28] K. Noguchi, O. Mitomi, and H. Miyazawa, "Millimeter-wave Ti:$LiNbO_3$ optical modulators," *J. Lightw. Technol.*, vol. 16, no. 4, pp. 615–619, Apr. 1998.

[29] R. G. Walker, "Electro-optic modulation at mm-wave frequencies in GaAs/AlGaAs guided wave devices," in *Proc. 8th IEEE LEOS Annu. Meeting*, San Francisco, CA, Oct. 1995, pp. 118–119.

[30] S. R. Sakamoto, R. Spickerman, and N. Dagli, "Novel narrow gap coplanar slow wave electrode for travelling wave electro-optic modulators," *Electron. Lett.*, vol. 31, no. 14, pp. 1183–1185, Jul. 1995.

[31] S. Thaniyavarn, G. Abbas, and W. Charczenko, "Very-low-loss electro-optic $LiNbO_3$ components for RF/Analog transmission," presented at the IEEE Avionics and Fiber Optics Conf., Minneapolis, MN, 2005, Paper ThC3.

[32] V. J. Urick, M. S. Rogge, F. Bucholtz, and K. J. Williams, "Wideband (0.045–6.25 GHz) 40 km analog fiber-optic link with ultra-high ($>$ 40 dB) all-photonic gain," *Electron. Lett.*, vol. 42, no. 9, pp. 552–553, Apr. 2006.

[33] J. H. Cole, M. M. Howerton, R. P. Moeller, J. Niemel, L. Cundin, and C. Sunderman, "Low drive voltage modulators with ultra low loss serpentine electrodes for electric field sensing with optical fibers," in *SPIE—17th Int. Conf. Optical Fibre Sensors Tech. Dig.*, 2005, vol. 5855, p. 371.

[34] C. C. Teng, "Travelling wave polymeric intensity modulator with more than 40 GHz 3 dB electrical bandwidth," *Appl. Phys. Lett.*, vol. 60, no. 13, pp. 1538–1540, Mar. 1992.

[35] D. Chen, H. Fetterman, A. Chen, W. H. Steier, L. R. Dalton, W. Wang, and Y. Shi, "Demonstration of 110 GHz electro-optic polymer modulators," *Appl. Phys. Lett.*, vol. 70, no. 25, pp. 3335–3337, Jun. 1997.

[36] T. Ido, S. Tanaka, M. Suzuki, M. Koizumi, H. Sano, and H. Inoue, "Ultra high-speed multiple quantum well electroabsorption optical modulators with integrated waveguides," *J. Lightw. Technol.*, vol. 14, no. 9, pp. 2026–2034, Sep. 1996.

[37] S. Z. Zhang, Y. J. Chiu, P. Abraham, and J. E. Bowers, "25 GHz polarisation insensitive electroabsorption modulators with travelling wave electrodes," *IEEE Photon. Technol. Lett.*, vol. 11, no. 2, pp. 191–193, Feb. 1999.

[38] G. L. Li, S. A. Pappert, C. K. Sun, W. S. C. Chang, and P. K. L. Yu, "Wide bandwidth travelling-wave InGaAsP/InP electro-absorption modulator for millimetre-wave applications," in *Proc. IEEE MTT-S Symp. Dig.*, May 2001, pp. 61–64.

[39] H. Kawanishi, Y. Yamauchi, N. Mineo, Y. Shibuya, H. Murai, K. Yamada, and H. Wada, "EAM-integrated DFB laser modules with more than 40 GHz bandwidth," *IEEE Photon. Technol. Lett.*, vol. 13, no. 9, pp. 954–956, Sep. 2001.

[40] Y. Zhuang, W. S. C. Chang, and P. K. L. Yu, "Peripheral-coupled-waveguide MQW electroabsorption modulator for near transparency and high spurious free dynamic range RF fiber-optic link," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2033–2035, Sep. 2004.

[41] Y. Inaba, H. Nakayama, M. Kito, M. Ishino, and K. Itoh, "High-power 1.55 μm mass-transport-grating DFB lasers for externally modulated systems," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 2, p. 152, Mar./Apr. 2001.

[42] J. J. Plant, P. W. Juodawlkis, R. B. Huang, J. P. Donnelly, L. J. Missaggia, and K. G. Ray, "1.5 μm InGaAsP-InP slab-coupled optical waveguide lasers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 735–737, Apr. 2005.

[43] T. J. Kane and R. L. Byer, "Monolithic unidirectional single mode Nd : YAG ring laser," *Opt. Lett.*, vol. 10, no. 2, pp. 65–67, Feb. 1985.

[44] C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, "Low-noise narrow-linewidth fiber laser at 1550 nm," *J. Lightw. Technol.*, vol. 22, no. 1, pp. 57–62, Jan. 2004.

[45] T. L. Boyd, D. Klemer, P. A. Leilabady, J. Noriega, and M. Pessot, "A 1.55 μm solid-state laser source for DWDM applications," *J. Lightw. Technol.*, vol. 17, no. 10, pp. 1904–1908, Oct. 1999.

[46] L. Piccari and P. Spano, "New method for measuring ultrawide frequency response of optical detectors," *Electron. Lett.*, vol. 18, no. 3, pp. 116–118, Feb. 1982.

[47] L. Goldberg, H. F. Taylor, J. F. Weller, and D. M. Bloom, "Microwave signal generation with injection locked laser diodes," *Electron. Lett.*, vol. 19, no. 13, pp. 491–493, Jun. 1983.

[48] B. Cai, D. Wake, and A. J. Seeds, "Microwave frequency synthesis using injection locked laser comb line selection," in *Proc. IEEE/LEOS Summer Topical Meeting RF Opto-Electron.*, Keystone, CO, Aug. 1995, pp. 13–14.

[49] S. Fukushima, C. F. C. Silva, Y. Muramoto, and A. J. Seeds, "10 to 110 GHz tuneable opto-electronic frequency synthesis using optical frequency comb generator and uni-travelling-carrier photodiode," *Electron. Lett.*, vol. 37, no. 12, pp. 780–781, Jun. 2001.

[50] C. Laperle, M. Svilans, M. Poirier, and M. Tetu, "Frequency multiplication of microwave signals by sideband optical injection locking using a monolithic dual-wavelength DFB laser device," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1219–1224, Jul. 1999.

[51] L. H. Enloe and J. L. Rodda, "Laser phase-locked loop," *Proc. IEEE*, vol. 53, no. 2, pp. 165–166, Feb. 1965.

[52] M. A. Grant, W. C. Michie, and M. J. Fletcher, "The performance of optical phase-locked loops in the presence of non-negligible loop propagation delay," *J. Lightw. Technol.*, vol. LT-5, no. 4, pp. 592–597, Apr. 1987.

[53] R. T. Ramos and A. J. Seeds, "Delay, linewidth and bandwidth limitations in optical phase-locked loops," *Electron. Lett.*, vol. 26, no. 6, pp. 389–391, Mar. 1990.

[54] K. J. Williams, L. Goldberg, and R. D. Esman, "6–34 GHz offset phase locking of Nd : YAG nonplanar ring lasers," *Electron. Lett.*, vol. 25, no. 18, pp. 1242–1243, Aug. 1989.

[55] L. G. Kazovsky and D. A. Atlas, "A 1300 nm experimental optical phase-locked loop," *IEEE Photon. Technol. Lett.*, vol. 1, no. 11, pp. 395–397, Nov. 1989.
[56] J. M. Khan, "1 Gb/s PSK homodyne transmission system using phase-locked semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 1, no. 10, pp. 340–342, Oct. 1989.
[57] M. Kourogi, C.-H. Shin, and M. Ohtsu, "A 134 MHz bandwidth homodyne optical phase locked loop of semiconductor laser diodes," *IEEE Photon. Technol. Lett.*, vol. 3, no. 3, pp. 270–272, Mar. 1991.
[58] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," *Electron. Lett.*, vol. 28, no. 1, pp. 82–83, Jan. 1992.
[59] U. Gliese, N. T. Nielsen, M. Bruun, E. L. Christensen, K. E. Stubkjaer, S. Lindgren, and B. Broberg, "A wideband heterodyne optical phase-locked loop for the generation of 3–18 GHz microwave carriers," *IEEE Photon. Technol. Lett.*, vol. 4, no. 8, pp. 936–938, Aug. 1992.
[60] L. N. Langley, M. D. Elkin, C. Edge, M. J. Wale, U. Gliese, X. Huang, and A. J. Seeds, "Packaged semiconductor laser optical phase-locked loop (OPLL) for photonic generation, processing and transmission of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1257–1264, Jul. 1999.
[61] A. C. Bordonalli, C. Walton, and A. J. Seeds, "High performance phase locking of wide linewidth semiconductor lasers by combined use of optical injection locking and optical phase-lock loop," *J. Lightw. Technol.*, vol. 17, no. 2, pp. 328–342, Feb. 1999.
[62] L. A. Johansson and A. J. Seeds, "Millimeter-wave modulated optical signal generation with high spectral purity and wide locking bandwidth using a fiber-integrated optical phase-lock loop," *IEEE Photon. Technol. Lett.*, vol. 12, no. 6, pp. 690–693, Jun. 2000.
[63] M. Ibsen, E. Ronnekliev, G. J. Cowle, M. N. Zervas, and R. I. Laming, "Multiple wavelength all fiber DFB lasers," *Electron. Lett.*, vol. 36, no. 2, pp. 143–144, Jan. 2000.
[64] A. C. Bordonalli, B. Cai, A. J. Seeds, and P. J. Williams, "Generation of microwave signals by active mode locking in a gain bandwidth restricted laser structure," *IEEE Photon. Technol. Lett.*, vol. 8, no. 1, pp. 151–153, Jan. 1996.
[65] E. Droge, E. H. Bottcher, S. Kollakowski, A. Strittmatter, O. Reimann, R. Steingruber, A. Umbach, and D. Bimberg, "Distributed MSM photodetectors for the long wavelength range," in *Proc. Eur. Conf. Opt. Commun.*, Oslo, Norway, 1998, vol. 1, pp. 20–24.
[66] C. Cohen-Jonathan, L. Giraudet, A. Bonzo, and J. P. Praseuth, "Waveguide AlInAs avalanche photodiode with a gain-bandwidth product of over 160 GHz," *Electron. Lett.*, vol. 33, no. 17, pp. 1492–1493, Aug. 1997.
[67] W. Gartner, "Depletion layer photoeffects in semiconductors," *Phys. Rev.*, vol. 116, no. 1, pp. 84–87, Oct. 1959.
[68] J. E. Bowers and C. A. Burrus, "High-speed zero-bias waveguide photodetectors," *Electron. Lett.*, vol. 22, no. 17, pp. 905–906, Aug. 1986.
[69] G. A. Davis, R. E. Weiss, R. A. LaRue, K. J. Williams, and R. D. Esman, "A 920–1650 nm high current photodetector," *IEEE Photon. Technol. Lett.*, vol. 8, no. 10, pp. 1373–1375, Oct. 1996.
[70] K. Kato, A. Kozen, Y. Muramoto, Y. Itaya, T. Nagatsuma, and M. Yaita, "110 GHz 50% efficiency mushroom mesa waveguide p-i-n photodiode for a 1.55 μm wavelength," *IEEE Photon. Technol. Lett.*, vol. 6, no. 6, pp. 719–721, Jun. 1994.
[71] M. Dentan and B. D. de Cremoux, "Numerical simulation of a p-i-n photodiode under high illumination," *J. Lightw. Technol.*, vol. 8, no. 8, pp. 1137–1144, Aug. 1990.
[72] P.-L. Liu, K. J. Williams, M. Y. Frankel, and R. D. Esman, "Saturation characteristics of fast photodetectors," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1297–1303, Jul. 1999.
[73] L. Y. Lin, M. C. Wu, T. Itoh, T. A. Vang, R. E. Muller, D. L. Sivco, and A. Y. Cho, "High power, high speed photodetectors design, analysis and experimental demonstration," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1320–1331, Aug. 1997.
[74] X. Li, N. Li, S. Demiguel, J. Campbell, D. Tulchinsky, and K. Williams, "A comparison of front- and backside-illuminated high-saturation power partially depleted absorber photodetectors," *IEEE J. Quantum Electron.*, vol. 40, no. 9, pp. 1321–1325, Sep. 2004.
[75] H. Ito, T. Furata, S. Kodama, and T. Ishibashi, "InP/InGaAs uni-travelling-carrier photodiode with 310 GHz bandwidth," *Electron. Lett.*, vol. 36, no. 21, pp. 1809–1810, Oct. 2000.
[76] K. J. Williams, "Nonlinear mechanisms in microwave photodetectors operated with high intrinsic region electric fields," *Appl. Phys. Lett.*, vol. 65, no. 10, pp. 1219–1221, Sep. 1994.
[77] K. J. Williams and R. D. Esman, "Photodiode dc and microwave nonlinearity at high current due to carrier recombination nonlinearities," *IEEE Photon. Technol. Lett.*, vol. 10, no. 7, pp. 1015–1017, Jul. 1998.
[78] K. J. Williams, R. D. Esman, and M. Dagenais, "Nonlinearities in p-i-n microwave photodetectors," *J. Lightw. Technol.*, vol. 14, no. 1, pp. 84–96, Jan. 1996.
[79] D. A. Tulchinsky, K. J. Williams, X. Li, N. Li, and J. C. Campbell, "High-power photodetectors," *IEEE LEOS Newslett.*, vol. 19, no. 2, pp. 16–17, Apr. 2005.
[80] A. Umbach, S. V. Waasen, U. Auer, H. G. Bach, R. M. Bertenburg, V. Breur, W. Ebert, G. Janssen, G. G. Mekonnen, W. Passenberg, W. Schlaak, C. Schraam, A. Seeger, G. J. Tegude, and G. Unterbosch, "Monolithic pin-HEMT 1.55 μm photoreceiver on InP with 27 GHz bandwidth," *Electron. Lett.*, vol. 32, no. 23, pp. 2142–2143, Nov. 1996.
[81] A. J. Seeds and A. A. A. de Salles, "Optical control of microwave semiconductor devices," *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 5, pp. 577–585, May 1990.
[82] A. A. A. de Salles, "Optical control of GaAs MESFETs," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-31, no. 10, pp. 812–820, 1983.
[83] R. N. Simons, "Microwave performance of an optically controlled AlGaAs/GaAs high electron mobility transistor and GaAs MESFET," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-35, no. 12, pp. 1444–1455, 1987.
[84] A. J. Seeds, J. F. Singleton, S. P. Brunt, and J. R. Forrest, "The optical control of IMPATT oscillators," *J. Lightw. Technol.*, vol. LT-5, no. 3, pp. 403–411, Mar. 1987.
[85] A. A. de Salles and J. R. Forrest, "Initial observations of optical injection locking of GaAs metal semiconductor field effect transistor oscillators," *Appl. Phys. Lett.*, vol. 38, no. 5, pp. 392–394, Mar. 1981.
[86] N. J. Gomes and A. J. Seeds, "Tunnelling metal-semiconductor contact optically pumped mixer," *Proc. Inst. Electr. Eng.*, vol. 136, no. 1, pp. 88–96, Feb. 1989.
[87] D. K. W. Lam and R. I. Macdonald, "GaAs optoelectronic mixer operation at 4.5 GHz," *IEEE Trans. Electron Devices*, vol. ED-31, no. 12, pp. 1766–1768, Dec. 1984.
[88] H. R. Fetterman and D. C. Ni, "Control of millimetre-wave devices by optical mixing," *Microw. Opt. Technol. Lett.*, vol. 1, no. 1, pp. 34–39, 1988.
[89] Z. Urey, D. Wake, D. J. Newson, and I. D. Henning, "Comparison of InGaAs transistors as optoelectronic mixers," *Electron. Lett.*, vol. 29, no. 20, pp. 1796–1798, Sep. 1993.
[90] Y. Betser, D. Ritter, C.-P. Liu, A. J. Seeds, and A. Madjar, "A single stage three terminal heterojunction bipolar transistor optoelectronic mixer," *J. Lightw. Technol.*, vol. 16, no. 4, pp. 605–609, Apr. 1998.
[91] C.-P. Liu, A. J. Seeds, and D. Wake, "Two-terminal edge-coupled InP/InGaAs heterojunction phototransistor opto-electronic mixer," *IEEE Microw. Guided Wave Lett.*, vol. 7, no. 3, pp. 72–74, Mar. 1997.
[92] A. J. Seeds, "Optical transmission of microwaves," in *Review of Radio Science*, W. R. Stone, Ed. Oxford, U.K.: Oxford Univ. Press, 1996, pp. 325–360.
[93] B. Cai and A. J. Seeds, "Optical frequency modulation links: Theory and experiments," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 4, pp. 505–511, Apr. 1997.
[94] R. D. Esman and K. J. Williams, "Wideband efficiency improvement of fiber optic systems by carrier subtraction," *IEEE Photon. Technol. Lett.*, vol. 7, no. 2, pp. 218–220, Feb. 1995.
[95] E. E. Funk, A. L. Campillo, and D. L. Tulchinsky, "Nonlinear distortion and crosstalk in microwave fiber-radio links," in *Proc. IEEE Microw. Symp. Dig.*, Jun. 2002, vol. 3, pp. 1691–1693.
[96] K. J. Williams, L. T. Nichols, and R. D. Esman, "Photodetector nonlinearity limitations on a high-dynamic range 3 GHz fiber optic link," *J. Lightw. Technol.*, vol. 16, no. 2, pp. 192–199, Feb. 1998.
[97] L. T. Nichols, K. J. Williams, and R. D. Esman, "Optimizing the ultrawide-band photonic link," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1384–1389, Aug. 1997.
[98] B. H. Kolner and D. W. Dolfi, "Intermodulation distortion and compression in an integrated electrooptic modulator," *Appl. Opt.*, vol. 26, no. 17, pp. 3676–3680, Sep. 1987.
[99] P. L. Liu, B. J. Li, and Y. S. Trisno, "In search of a linear electrooptic amplitude modulator," *IEEE Photon. Technol. Lett.*, vol. 3, no. 2, pp. 144–146, Feb. 1991.
[100] W. K. Burns, "Linearized optical modulator with fifth order correction," *J. Lightw. Technol.*, vol. 13, no. 8, pp. 1724–1727, Aug. 1995.

[101] W. B. Bridges and J. H. Schaffner, "Distortion in linearized electrooptic modulators," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2184–2197, Sep. 1995.

[102] C. D. Zaglanikis and A. J. Seeds, "Computer model for semiconductor laser amplifiers with RF intensity-modulated inputs," *Proc. Inst. Electr. Eng.*, vol. 139, no. 4, pp. 254–262, Aug. 1992.

[103] R. J. Mears, L. Reekie, S. B. Poole, and D. N. Payne, "Low-noise erbium-doped fiber amplifier operating at 1.54 μm," *Electron. Lett.*, vol. 23, no. 19, pp. 1026–1028, Sep. 1987.

[104] J. D. Ingham *et al.*, "Wide-frequency-range operation of a high linearity uncooled DFB laser for next-generation radio-over-fiber," in *Proc. IEEE/OSA OFC*, Atlanta, GA, 2003, pp. 754–756.

[105] T. Niiho *et al.*, "Multi-channel wireless LAN distributed antenna system based on radio-over-fiber techniques," in *Proc. IEEE LEOS Annu. Meeting*. Rio Grande, Puerto Rico, 2004, pp. 57–58.

[106] D. Wake, D. Johansson, and D. G. Moodie, "Passive picocell—A new concept in wireless network infrastructure," *Electron. Lett.*, vol. 33, no. 5, pp. 404–406, Feb. 1997.

[107] C. Liu *et al.*, "Bi-directional transmission of broadband 5.2 GHz wireless signals over fiber using a multiple-quantum-well asymmetric Fabry–Pérot modulator/photodetector," in *Proc. IEEE/OSA OFC*, Atlanta, GA, 2003, pp. 738–740.

[108] LG cell product description. [Online]. Available: http://www.lgcwireless.com/products/lgcell.html

[109] P. Hartmann *et al.*, "Low-cost multimode fiber-based wireless LAN distribution system using uncooled directly modulated DFB laser diodes," in *Proc. ECOC*, Rimini, Italy, 2003, pp. 804–805.

[110] H. Ogawa, D. Polifko, and S. Bamba, "Millimetre-wave fiber optic systems for personal radio communication," *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 12, pp. 2285–2292, Dec. 1992.

[111] H. Schmuck and R. Heidemann, "High capacity hybrid fiber-radio field experiments at 60 GHz," in *Proc. IEEE/IEICE MWP*, Kyoto, Japan, 1996, pp. 65–68.

[112] K. Kitayama, "Fading-free transport of 60 GHz optical DSB signal in non-dispersion shifted fiber using chirped fiber grating," in *Proc. IEEE MWP*, Princeton, NJ, 1998, pp. 223–226.

[113] J. J. O'Reilly, P. M. Lane, and M. H. Capstick, "Optical generation and delivery of modulated mm-waves for mobile communications," in *Analogue Optical Fiber Communications*, B. Wilson, Z. Ghassemlooy, and I. Darwazeh, Eds. London, U.K.: Inst. Electr. Eng., 1995, pp. 229–256.

[114] G. H. Smith and D. Novak, "Broadband millimetre-wave (38 GHz) fiber-wireless transmission system using electrical and optical SSB modulation to overcome dispersion effects," *IEEE Photon. Techol. Lett.*, vol. 10, no. 1, pp. 141–143, Jan. 1998.

[115] K. I. Kitayama, T. Kuri, H. Yokoyama, and M. Okuno, "60 GHz millimetre-wave generation and transport over OFDM fiber-optic networks," in *Proc. IEEE/IEICE MWP*, Kyoto, Japan, 1996, pp. 49–52.

[116] R. P. Braun, G. Grosskopf, D. Rohde, and F. Schmidt, "Fiber optic millimetre-wave generation and bandwidth efficient data transmission for broadband mobile 18–20 and 60 GHz band communications," in *Proc. IEEE MWP*, Essen, Germany, 1997, pp. 235–238.

[117] L. A. Johansson, D. Wake, and J. Seeds, "Millimetre-wave over fiber transmission using a BPSK reference modulated optical injection phase lock loop," in *Proc. IEEE/OSA OFC*, Anaheim, CA, Mar. 2001, vol. 3, pp. WV3-1–WV3-3.

[118] T. E. Darcie and G. E. Bodeep, "Lightwave subcarrier CATV transmission systems," *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 5, pp. 524–533, May 1990.

[119] P. A. Davies and N. J. Gomes, "Subcarrier multiplexing in optical communication network," in *Analogue Optical Fiber Communications*, B. Wilson, Z. Ghassemlooy, and I. Darwazeh, Eds. London, U.K.: Inst. Electr. Eng., 1995, pp. 1–32.

[120] F. Deborgies, G. Chevalier, Y. Combemale, P. Maillot, P. Richin, P. Blanchard, and O. Mass, "100 μs microwave optical delay line using directly modulated lasers," in *Proc. 20th Eur. Microw. Conf.*, Budapest, Hungary, 1990, pp. 677–680.

[121] I. L. Newberg, C. M. Gee, G. D. Thurmond, and H. W. Yen, "Long microwave delay fiber-optic link for radar testing," *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 5, pp. 664–666, May 1990.

[122] B. Moslehi, J. Goodman, M. Tur, and H. J. Shaw, "Fiber optic lattice signal processing," *Proc. IEEE*, vol. 72, no. 7, pp. 909–930, Jul. 1984.

[123] J. Capmany, D. Pastor, and B. Ortega, "New and flexible fiber optic delay line filters using chirped Bragg gratings and laser arrays," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1321–1326, Jul. 1999.

[124] K. Takada, M. Abe, T. Shibata, and K. Okamoto, "1 GHz-spaced 16-channel arrayed-waveguide grating for a wavelength reference standard in DWDM network systems," *J. Lightw. Technol.*, vol. 20, no. 5, pp. 850–853, May 2002.

[125] B. E. Little, S. T. Chu, P. P. Absil, J. V. Hryniewicz, F. G. Johnson, F. Seiferth, D. Gill, V. Van, O. King, and M. Trakalo, "Very high-order microring resonator filters for WDM applications," *IEEE Photon. Technol. Lett.*, vol. 16, no. 10, pp. 2263–2265, Oct. 2004.

[126] C. Ming, G. Junziker, and K. Vahala, "Fiber-optic add–drop device based on a silica microsphere-whispering gallery mode system," *IEEE Photon. Technol. Lett.*, vol. 11, no. 6, pp. 686–687, Jun. 1999.

[127] A. C. Lindsay, G. A. Knight, and S. T. Winnall, "Photonic mixers for wide bandwidth RF receiver applications," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2311–2317, Sep. 1995.

[128] L. J. Mullen, C. Vieira, P. R. Herczfeld, and V. M. Contarino, "Application of RADAR technology to aerial LIDAR systems for enhancement of shallow underwater target detection," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2370–2377, Sep. 1990.

[129] K. J. Williams and R. D. Esman, "Optically amplified downconverting link with shot-noise-limited performance," *IEEE Photon. Technol. Lett.*, vol. 8, no. 1, pp. 148–150, Jan. 1996.

[130] S. J. Strutz and K. J. Williams, "A 0.8–8.8 GHz image rejection microwave photonic downconverter," *IEEE Photon. Technol. Lett.*, vol. 12, no. 10, pp. 1376–1378, Oct. 2000.

[131] S. T. Winnall, K. L. Mahady, D. B. Hunter, and A. C. Lindsay, "An optically amplified four-channel WDM downconvertor for wideband microwave receiver applications," in *Proc. IEEE MWP*, Sep. 11, 2000, pp. 175–178.

[132] J. R. Forrest, F. P. Richards, A. A. Salles, and P. Varnish, "Optical fiber networks for signal distribution and control in phased array radars," in *Proc. Int. Conf. Radar, Radar*, London, U.K., 1982, pp. 408–412.

[133] A. J. Seeds, "Optical technologies for phased array antennas," *IEICE Trans. Electron.*, vol. E76-C, pp. 198–206, 1993.

[134] W. S. Birkmayer and M. J. Wale, "Proof of concept model of a coherent optical beam forming network," *Proc. Inst. Electr. Eng.*, vol. 139, no. 4, pp. 301–304, Aug. 1992.

[135] R. A. Wilson, P. Sample, A. Johnstone, and M. F. Lewis, "Phased array antenna beamforming using a micromachined silicon spatial light modulator," in *Proc. IEEE/IEE MWP*, Oxford, U.K., 2000, pp. 23–26.

[136] J. Stulemeijer, R. van Dijk, F. E. van Vliet, D. H. P. Maat, and M. K. Smit, "Photonic chip for steering a four element phased array antenna," in *Proc. IEEE/IEE MWP*, Oxford, U.K., 2000, pp. 20–22.

[137] W. Ng, A. A. Walston, G. L. Tangonan, J. J. Lee, I. L. Newberg, and N. Bernstein, "The first demonstration of an optically steered microwave phased array using true time delay," *J. Lightw. Technol.*, vol. 9, no. 9, pp. 1124–1131, Sep. 1991.

[138] D. Dolfi, F. Michel-Gabriel, S. Bann, and J. P. Huignard, "Two dimensional optical architecture for time delay beam forming in a phased array antenna," *Opt. Lett.*, vol. 16, no. 4, pp. 255–257, Feb. 1991.

[139] M. Y. Frankel and R. D. Esman, "True time-delay fiber-optic control of an ultrawideband array transmitter/receiver with multibeam capability," *IEEE Trans. Microw. Theory Technol.*, vol. 43, no. 9, pp. 2387–2394, Sep. 1995.

[140] A. Molony, L. Zhang, J. A. R. Williams, I. Bennion, C. Edge, and J. Fells, "Fiber Bragg grating true time delay systems: Discrete grating array 3-b delay lines and chirped grating 6-b delay lines," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1527–1530, Aug. 1997.

[141] T. R. Clark, J. U. Kang, and R. D. Esman, "Performance of a time- and wavelength-interleaved photonic sampler for analogue to digital conversion," *IEEE Photon. Technol. Lett.*, vol. 11, no. 9, pp. 1168–1170, Sep. 1999.

[142] F. Coppinger, A. S. Bhushan, and B. Jalali, "12 Gsample/s wavelength division sampling analogue to digital converter," *Electron. Lett.*, vol. 36, no. 4, pp. 316–318, Feb. 2000.

[143] W. Ng, R. Stephens, D. Persechini, and K. V. Reddy, "Ultra-low jitter mode-locking of an Er-fiber laser at 10 GHz and its application in photonic analog to digital conversion," in *Proc. IEEE/IEE MWP*, Oxford, U.K., 2000, pp. 251–254.

[144] A. S. Daryoush, "Phase coherency of generated millimeter wave signals using fiber optic distribution of a reference," in *Proc. IEEE/IEICE MWP*, Kyoto, Japan, 1996, pp. 225–228.

[145] M. Kourogi, T. Enami, and M. Ohtsu, "A monolithic optical frequency comb generator," *IEEE Photon. Technol. Lett.*, vol. 6, no. 2, pp. 214–217, Feb. 1994.

[146] A. J. Seeds, C. Renaud, M. Pantouvaki, M. Robertson, D. Rogers, and P. J. Cannard, "Efficient photonic THz generation, IEICE 2006 Asia-pacific microwave photonics conference," in *Proc. AP-MWP*, Kobe, Japan, 2006, pp. 257–268.
[147] M. F. Lewis, "Novel RF oscillator using optical components," *Electron. Lett.*, vol. 28, no. 1, pp. 31–32, Jan. 1992.
[148] X. S. Yao and L. Maleki, "Opto-electronic oscillator and its applications," in *Proc. MWP*, Kyoto, Japan, 1996, pp. 265–268.
[149] W. Zhou and G. Blasche, "Injection-locked dual opto-electronic oscillator with ultra-low phase noise and ultra-low spurious level," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, p. 929, Mar. 2005.
[150] E. N. Ivanov, S. A. Diddams, and L. Hollberg, "Analysis of noise mechanisms limiting the frequency stability of microwave signals generated with a femtosecond laser," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 4, p. 1072, Jul./Aug. 2003.
[151] S. A. Diddams, A. Bartels, T. M. Ramond, C. W. Oates, S. Bize, E. A. Curtis, J. C. Bergquist, and L. Hollberg, "Design and control of femtosecond lasers for optical clocks and the synthesis of low-noise optical and microwave signals," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 4, pp. 1072–1080, Jul./Aug. 2003.
[152] G. David, P. Bussek, U. Auer, F. J. Tegude, and D. Jager, "Electro-optic probing of RF signals in submicrometre MMIC devices," *Electron. Lett.*, vol. 31, no. 25, pp. 2188–2189, Dec. 1995.
[153] T. Nagatsuma, "Progress of instrumentation and measurement towards millimetre-wave photonics," in *Proc. IEEE MWP*, Melbourne, Australia, 1999, pp. 91–94.
[154] G. Maury, A. Hilt, T. Berceli, B. Cabon, and A. Vilcot, "Microwave frequency conversion methods by optical interferometer and photodiode," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1481–1485, Aug. 1997.

Alwyn J. Seeds (M'81–SM'92–F'97) received the Ph.D. and D.Sc. degrees from the University of London, London, U.K.

From 1980 to 1983, he was a Staff Member with Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, where he worked on GaAs monolithic millimeter-wave integrated circuits for use in phased-array radar. He returned to England in 1983 to take up a lectureship in telecommunications at Queen Mary College, University of London, moving to University College London in 1986, where he is currently Professor of opto-electronics and Head of the Photonics Group. He has published over 250 papers on microwave and opto-electronic devices and their systems applications and is Presenter of the video "Microwave Opto-electronics" in the IEEE Emerging Technologies series. His current research interests include microwave bandwidth tunable semiconductor lasers, semiconductor optical modulators, mode-locked lasers, optical phase-lock loops, optical frequency synthesis, broadband wireless-over-fiber access systems, dense WDM networks, terahertz photonics, and nonlinear optical devices.

Prof. Seeds is Chairman of the Photonics Professional Network of the Institution of Engineering and Technology, U.K., a Fellow of the Royal Academy of Engineering, and a member of the Technical Committee on Microwave Photonics of the IEEE Laser and Electro-optics Society. He has served on the program committees for many international conferences. He is a Cofounder of ZinWave Inc.: a manufacturer of wireless-over-fiber systems.

Keith J. Williams (S'86–M'89) received the B.S. degree in electrical engineering (*cum laude*) from the University of Nebraska, Lincoln, in 1987 and the M.S. and Ph.D. degrees in electrical engineering from the University of Maryland, College Park, in 1989 and 1994, respectively. His doctoral dissertation research was conducted in the area of microwave p-i-n photodetector nonlinearities.

In 1987, he joined the Optical Techniques Branch of the Naval Research Laboratory (NRL), Washington, DC, where his research interests include characterization and performance of microwave-optical devices, microwave fiber-optic links and systems, high-speed optoelectronics, new concepts for solving microwave-related problems with fiber-optic solutions, and high-current photodiodes. He is currently Head of the Photonics Technology Branch at NRL, which includes research on microwave photonics, optical communications, integrated optics, laser and amplifier development, and information technologies.

Dr. Williams is a member of the Optical Society of America and Tau Beta Pi.