# Microwave Photonics

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*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 describes the development of microwave photonic devices, describes their systems applications, and suggests likely areas for future development.**

***Index Terms*—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 rates. Second, the use of opto-electronic devices and systems for signal handling in microwave systems. 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 deployed long-distance systems having minimum channel rates of 10 Gb/s and the evolution of the ethernet standard to encompass a transmission rate of 10 Gb/s [1], 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, and radio astronomy.

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, while Section IV will describe applications to microwave systems. Finally, Section V 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, Murray Hill, NJ [2] and the continuously operating helium neon laser at Bell Laboratories, Malibu, CA [3] 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 [4] and Johnson [5], while frequencies as high as 11 GHz were being achieved by the early 1970s [6].

Greater compactness was offered by the semiconductor laser, and with the development of double heterostructure devices capable of room-temperature continuous operation in 1970 [7], [8], 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 [9].

For transmission, early plans were based on free-space optics and gas lenses [10], but following predictions [11] and realization [12] 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 at 1300 nm and later at 1500 nm [13], [14].

For detection, fast depletion and avalanche detectors were developed at an early stage [15], [17] and subsequently developed to give useful microwave bandwidth response [16], [18]. Direct optical control of microwave devices was also investigated, with early demonstrations of tuning of Gunn oscillators [19], tuning and power modulation of TRAPATT oscillators [20], and tuning of IMPATT oscillators [21], [22] by optical illumination. Injection locking of bipolar transistor [23] and IMPATT oscillators [24] to intensity modulated optical signals was also achieved. Fig. 1 shows the measured locking behavior of an edge-illuminated silicon 7.8-GHz IMPATT oscillator to a directly modulated GaAs/AlGaAs laser. A locking range of about 1 MHz was obtained.

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 [25]–[27] with a variety of pioneering demonstrations.

## III. Technologies

### A. Source Technologies

*1) Directly Modulated Semiconductor Lasers:* The simplicity of direct modulation of semiconductor lasers has proved

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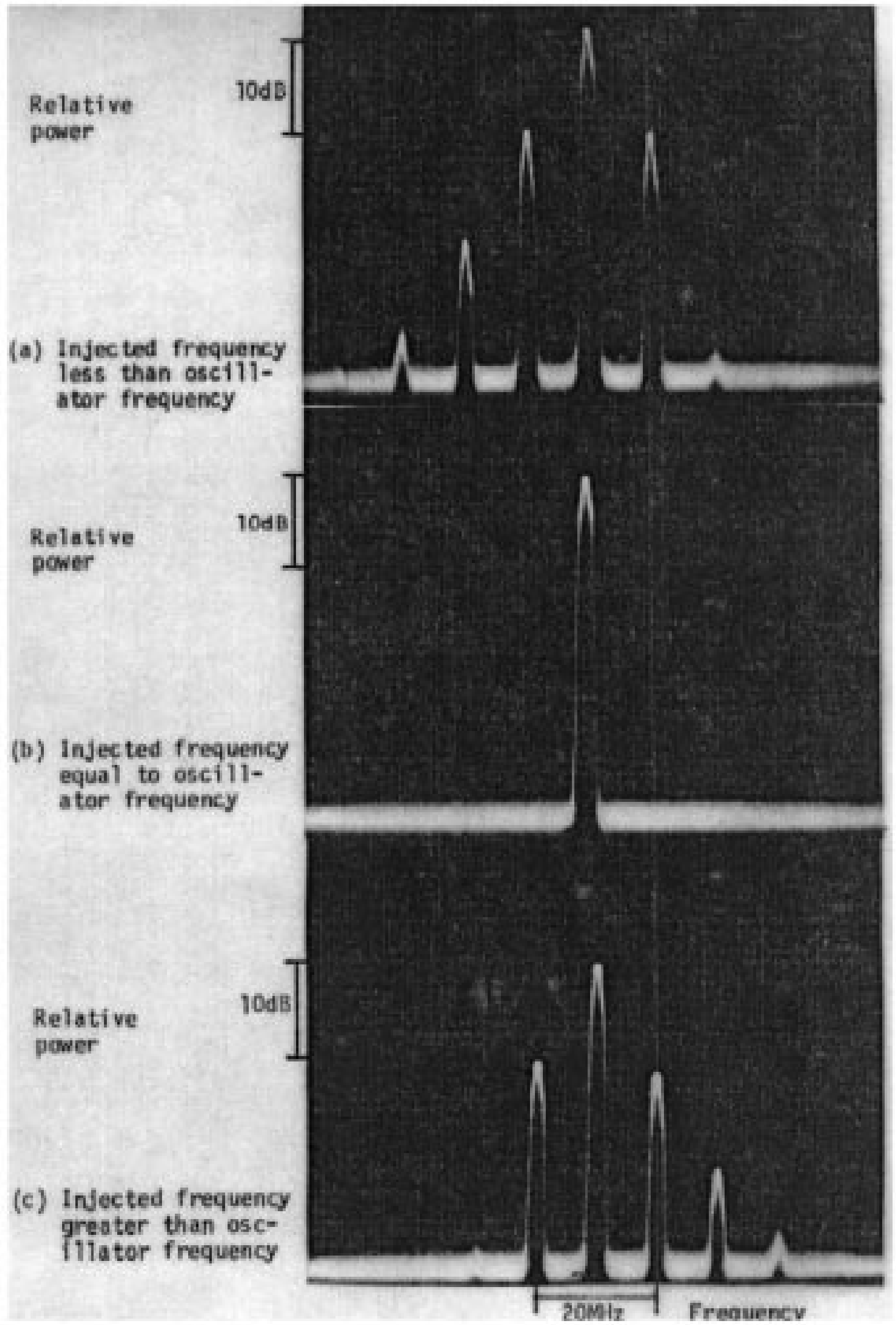



Fig. 1. Spectrum analyzer displays showing optical injection locking of a silicon IMPATT oscillator (after [24]).

attractive for many applications and, following early work on modulation characteristics [9], 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 $\omega_p$, above which the undamped detected electrical response falls as $1/\omega_m^4$, where $\omega_m$ is the modulating frequency. $\omega_p$ can be approximated by

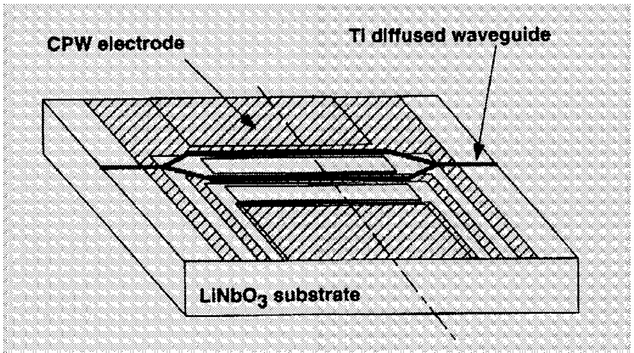
$$\omega_p = \sqrt{\frac{g_o S_o}{\tau_p(1+\varepsilon S_o)}} \tag{1}$$

where $g_o$ is the differential gain, $S_o$ is the mean photon density, $\tau_p$ is the photon lifetime, and $\varepsilon$ is 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. An important limitation is gain compression, which has thus far limited reliable 1.55-$\mu$m room-temperature operation lasers to bandwidths less than 30 GHz [28] despite much research effort.

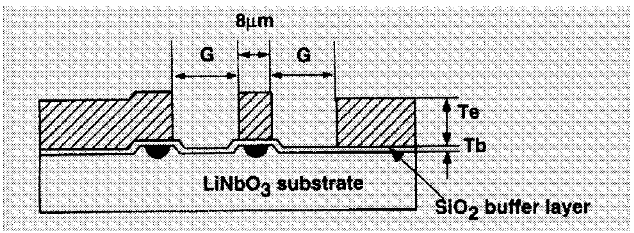
*2) External Modulators:* The modulated component of the optical power output of an optical modulator can be written

$$P_{om} = k_m V_i P_{op} \tag{2}$$

where $k_m$ is the modulation sensitivity $(\mathrm{V}^{-1})$, $V_i$ is the modulating signal voltage, and $P_{op}$ is the unmodulated optical




(a)




(b)

Fig. 2. (a) Top view and (b) cross section of millimeter-wave Ti : $LiNbO_3$ Mach–Zehnder modulator [30].

input 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 [29].

Interferometric modulators using lithium–niobate and GaAs technologies have been realized with −3-dB electrical bandwidths in excess of 40 GHz [30]–[32]. Fig. 2 shows the construction of a millimeter-wave bandwidth lithium–niobate modulator. A 2-cm-length modulator of this design demonstrated a −3-dB electrical bandwidth of over 70 GHz with an extinction voltage $V_\pi$ of 5.1 V [30]. Fiber-to-fiber insertion loss including connectors for a packaged 3-cm-length modulator of similar design was 5.6 dB. Impressive results have also been shown for the GaAs system with −3-dB electrical bandwidths of over 50 GHz and $V_\pi$ of 13 V for a 1-cm-long modulator [31]. 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 of order 10 dB. Recently, there has been strong interest in electrooptic polymer modulators with −3-dB electrical bandwidths exceeding 40 GHz, $V_\pi$ values of 10 V and fiber-to-fiber insertion losses of 10 dB being obtained [33]. Operation at 110 GHz has also been demonstrated [34]. There is evidence that problems of optical power handling, stability, and high-temperature operation are being overcome, making this technology one of considerable interest.

Electro-absorption modulators operate by converting the incident light into photo-current 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 1.53 $\mu$m 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 [35]. To obtain sufficiently low capacitance for such high-speed operation, the active section of the waveguide must be kept very short, 50 $\mu$m in this example, limiting the modulation sensitivity. Traveling-wave approaches can be used to improve this parameter [36], [37] and a 1.3-$\mu$m traveling-wave modulator with −3-dB electrical bandwidth exceeding 5–40 GHz, small-signal modulation sensitivity 0.65 $V^{-1}$, and fiber-to-fiber insertion loss of 11.3 dB has been recently demonstrated [37]. 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 [38].

*3) Heterodyne Sources:* Consider two monochromatic optical sources emitting at frequencies $\omega_1$ and $\omega_2$, 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

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

where $P_1$ and $P_2$ are the powers and $\phi_1$ and $\phi_2$ 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 third window optical communications typically emit at frequencies 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 [39]; however, the large free-running linewidth of nonline narrowed semiconductor lasers (typically 1–50 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 a spectrally pure microwave heterodyne signal. Goldberg *et al.* [40] 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 [41], [117]. 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 millikelvin precision, or lasers must be monolithically integrated to achieve thermal tracking [42].

An alternative technique for correlating the phase noise of the heterodyne sources is to use an optical phase-lock loop (OPLL) [43]–[52]. Fig. 3 shows the experimental arrangement required [50]. 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

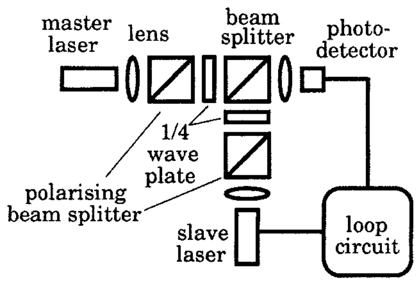



Fig. 3. Heterodyne OPLL (after [50]).

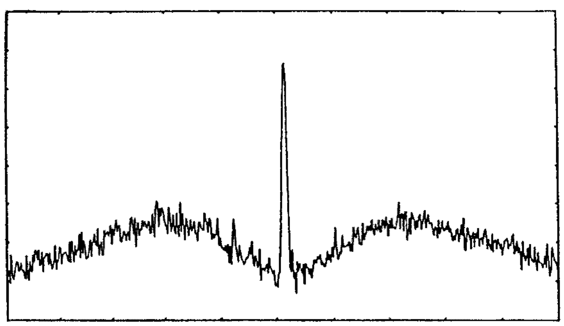


Fig. 4. Output spectrum of packaged OPLL (vertical scale: 5 dB/div., horizontal scale: 10 MHz/div., resolution bandwidth: 300 kHz) (after [50]).

exactly equals that of the reference. Although simple in principle and demonstrated for narrow-linewidth gas lasers at an early stage in laser development [43], the practical realization of OPPLs 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 [44], [45]. The requirement for subnanosecond loop delays to lock nonline narrowed semiconductor lasers led to much early work being carried out with narrow-linewidth solid-state [46], [47] or external cavity semiconductor [48] lasers. Nevertheless, by careful microoptical design, first homodyne [49] and, subsequently, heterodyne [50], [51] loops were successfully realized using nonline narrowed semiconductor lasers with linewidths of an order of 10 MHz, yielding reference source limited phase noise of better than −83 dBc/Hz at offsets of a few megahertz, as shown in Fig. 4. More recently, such loops have been ruggedly packaged for use in phased-array antenna applications [52].

A method of overcoming the requirement for short loop propagation delay and, hence, microoptical construction when using nonline-narrowed semiconductor lasers, is to combine injection locking with a phase-lock loop, forming an optical injection phase-lock loop (OIPLL) [53]. Here, control of close to carrier phase noise and laser frequency drift is through the phase-lock loop path, while wide-band phase-noise suppression is achieved through the injection locking path. Implementations of such loops with fiber pigtailed 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 [54].

A multimode single laser can also be used as an heterodyne signal source [55], [56]. For semiconductor lasers, microwave modulation of the injection current and, hence, gain, provides a convenient method of locking the heterodyne frequency [56]. Tuning ranges of such sources are typically less than 10% of the heterodyne frequency.

### *B. Detection Technologies*

*1) Photodetectors:* Metal–semiconductor–metal (MSM) photodetectors have been used in a number of microwave photonic applications. The main attraction has been their compatibility for integration with field-effect-transistor devices in optically controlled monolithic microwave integrated circuits (MMICs). Bandwidths as high as 78 GHz have been reported [57] 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 1.55 $\mu$m [58].

The upper limit to depletion photodiode frequency response is set by transit time effects [59] and by the depletion capacitance of the diode. Optimization involves conflicting requirements since reducing the depletion width to increase the transit time limited frequency increases the depletion capacitance and may lead to incomplete absorption of light in geometries where light is incident normal to the junction plane. For high-speed operation, waveguide photodiodes with light incident parallel to the junction plane have been extensively studied [60], with multimode designs offering 110-GHz bandwidth with 50% quantum efficiency [61]. The depletion capacitance limit can be circumvented by applying traveling-wave design techniques [62].

In 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 that has been studied theoretically [63] and experimentally [64]. Traveling-wave configurations can be used to reduce the space charge density and obtain increased power-handling capability [65]. It is also possible to increase power handling by making use of carrier velocity overshoot effects as in the uni-traveling-carrier photodiode (UTC-PD) [66]. Fig. 5 shows the energy band diagram for the structure. The absorption and drift regions are separate and the absorption region is doped so that the holes are majority carriers. The electrons are injected at high energy into the thin drift region where they travel at overshoot velocity, typically five times static saturated drift velocity, thus giving rise to much reduced space charge for a given terminal current. UTC-PDs have been reported with bandwidths exceeding 300 GHz [66] and output powers exceeding 8 dBm [67].

Interfacing of photodiodes with subsequent amplifiers can be eased by monolithic integration, and impressive demonstrations of this have already been reported [68].

*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

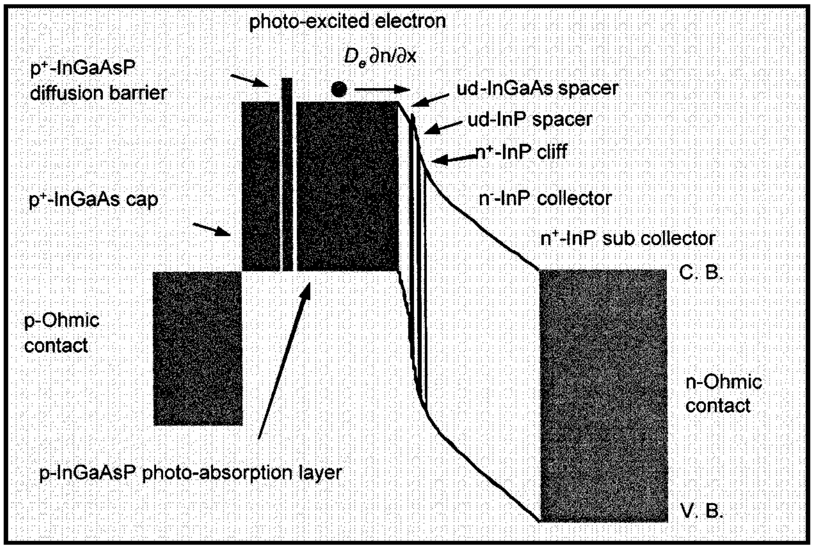



Fig. 5. Energy band diagram of UTC-PD (after [67]).

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 photo-generation 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 [69]; some of the more important examples are described below, together with some recent developments.

*a) Amplifiers:* The gain of microwave MESFETs and high electron-mobility transistors (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 [70]. 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 7–10 times higher [71].

*b) 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 [72], MESFETs [73], and bipolar transistors [23]. 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.

*c) Opto-Electronic Mixers:* Two configurations are possible. 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 [74]. The converse arrangement in which an electrical local-oscillator signal is used to down-convert an intensity-modulated optical signal has also been demonstrated [75]. 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. Opto-electronic mixers have been realized using photoconductive devices [75], diodes [74], field-effect transistors [76], and bipolar transistors [77]. Much improved optical control response has been demonstrated using heterostructure bipolar transistors in either normal incidence [78] or edge-illuminated [79] configurations.

## IV. Applications

### A. Transmission and Antenna Remoting

Interest in the use of optical techniques for wide-band signal transmission arises directly from the low transmission loss possible in optical fiber compared with electrical media. In order to avoid the modal noise problems characteristic of multimode fiber systems, single-mode fiber is used in most microwave photonic systems. Table I gives loss and dispersion values for silica fiber at the three most used transmission wavelengths. 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

TABLE I
LOSS AND DISPERSION OF SILICA OPTICAL FIBER

| Wavelength (nm) | Loss (dB/km) | Dispersion (ps/km/nm) |
|---|---|---|
| 850 | 2.0 | 90 |
| 1,300 | 0.4 | <4 |
| 1,550 | 0.2 | <17 |

antenna remoting, 1300–1600-nm wavelength 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 of a microwave photonic link without embedded electrical amplification is given by [80]

$$\mathrm{SNR} = \frac{(mRP_{op}G_{ot})^2}{2B\left[N_L(RP_{op}G_{ot})^2 + \overline{i_{na}^2}\Big/B + 2eRG_{ot}P_{op} + \dfrac{4kT}{R_L}\right]} \tag{4}$$

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, $N_L$ is the laser relative intensity noise (RIN), $\overline{i_{na}^2}$ is the mean squared output noise current due to 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 signal-to-noise ratio can be increased by increasing the unmodulated optical power $P_{op}$ until either the RIN or shot noise limit is reached. By this means it is possible to construct links having gain and noise figures of a few decibels without the use of electrical amplification [29], [81]. For long links (>20 km), where fiber nonlinearity restricts the fiber launch power, high signal-to-noise ratio can still be obtained by using optical angle modulation [82].

For indoor and other short-range applications, electro-absorption modulators, as described in Section III-A (2), can be used as combined detectors and modulators, producing a passive picocell system [83]. Fig. 6 shows the arrangement used. The downlink signal generates photocurrent in the modulator, which drives the antenna. The received uplink signals modulate the light passing through the modulator, which is then fed back to the central station and photodetected.

At frequencies above those for which directly modulation or external modulators are appropriate, a wide variety of techniques have been investigated [84]–[90] to provide broad-band fiber radio access with resistance to the fiber dispersion penalties resulting from the high carrier frequency. These include dispersion compensation [86], frequency multiplying modulators with sideband filtering for modulation [87], optical single-sideband modulators [88], 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-A (3) [90]. Of these methods, dispersion compensation requires adjustment if the fiber span length is changed; modulator approaches suffer substantial optical loss, whereas the power output at the required modulation frequency from mode-locked lasers is usually small

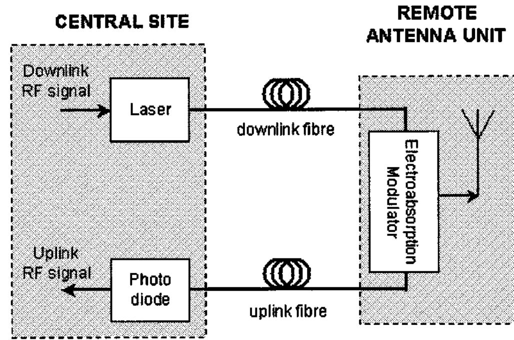



Fig. 6. Passive picocell transmission system (after [83]).

so that optical amplifiers are required, increasing system cost. Injection-locking approaches offer high launch power, reducing the need for optical amplifiers, but require millikelvin temperature control of the slave lasers for reliable operation. Use of the OIPPL technique described in Section III-A (4) overcomes these limitations [91].

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 laser amplifier (SLA) [92] and the doped fiber amplifier (DFA) [93]. The DFA 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 kilohertz region, whereas SLAs generally show substantial distortion below a few hundred megahertz due to the nanosecond order carrier lifetime.

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

The cable television industry is also using broad-band fiber technology for signal distribution [94]. Each 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 [95].

### *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.* [96] report a 100-$\mu$s optical fiber delay line with a directly modulated semiconductor laser source for use up to 8 GHz. Signal-to-noise ratio exceeds 127 dB $\cdot$ Hz up to 4 GHz, falling to 115 dB $\cdot$ 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

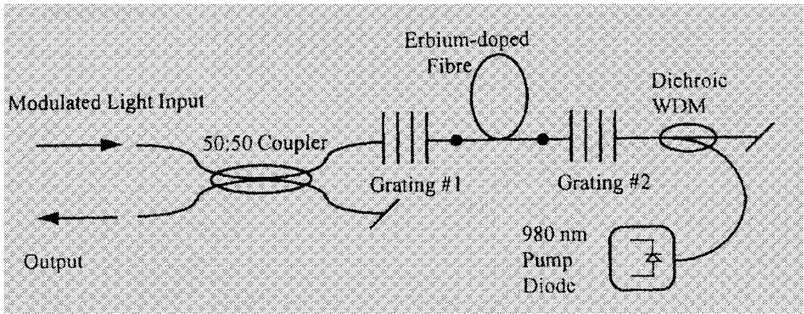



Fig. 7. Amplified fiber Bragg grating Fabry–Perot filter [99].

greater than 1 GHz. Such delay lines are useful in radar target simulators [97].

Transversal filters using fiber delay lines have been extensively investigated [98] and the development of DFA and fiber Bragg grating technology has considerably widened the possibilities for filter synthesis [99], [100]. Fig. 7 shows an amplified fiber Fabry–Perot filter where the $Q$ can be set by changing the pump power [99]. A $Q$ of 325 was obtained at a center frequency of about 1 GHz.

Multioctave bandwidth signal-processing receiver design with improved rejection of intermodulation and spurious responses has been demonstrated by using optical modulators as photonic mixers [101]. 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 [102].

### C. 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 MMICs 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 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 [103] and, more recently, for beam forming [104].

Technologies for optical beam forming are shaped by the lack of fast ($<$1 ns) low-loss ($<$1 dB) optical switches and application requirements for instantaneous bandwidth. For most communications applications, very wide ($>$20% of center frequency) bandwidths are not required and antenna apertures are modest. Coherent beam forming, using the heterodyne approach of Section III-A (3) with phase shift applied to one source only then becomes attractive [105]. Significant progress has been made in integrating the beam-former functions in GaAs and $LiNbO_3$ [105] in silicon [106] and in InP [107] technologies.

For applications such as wide-band 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 [108] and two-dimensional free-space optics [109]. Fig. 8 shows a method using a tunable laser and an array of fibers having different dispersion values [110]. 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 [111].

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 [112]–[114]. Representative results achieved thus far include 8-bit spurious-free dynamic range at 10 Gsample/s [114].

### D. Other Applications

With the availability of sub-millimeter-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. For these applications, phase noise requires careful attention [115]. Signals at frequencies $>$1 THz locked to a microwave reference can be generated using optical comb generators [116]. Combining optical comb generation with injection-locked comb-line selection has allowed optical synthesis of signals from 10 to 110 GHz to be demonstrated [117]. Fig. 9 shows how such a system might be applied to local-oscillator generation for radio-astronomy applications.

The long delay and low loss possible in optical fiber can also be used to produce low phase-noise microwave oscillators [118], [119].

Opto-electronic probing of microwave and ultrafast digital integrated circuits offers unique low invasive characterization at millimeter-wave frequencies and above [120], [121] and has now been developed to a state where ease of use is comparable to conventional network analysis.

## V. 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

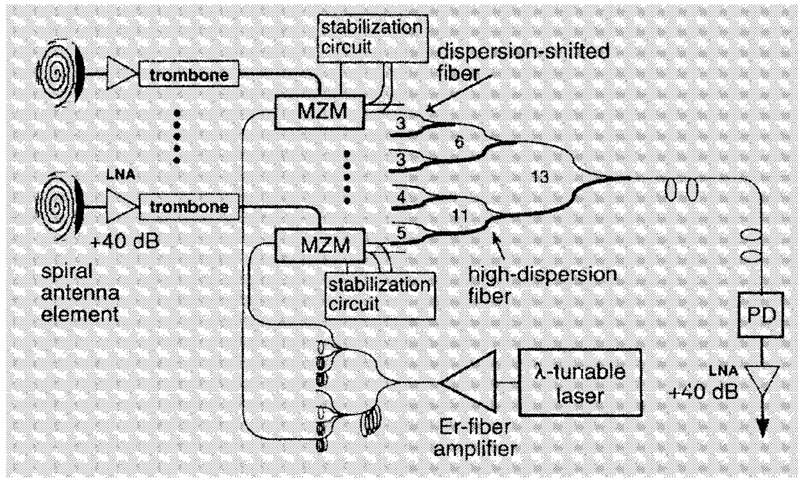



Fig. 8. True time-delay receive beam former using dispersive fiber [110].

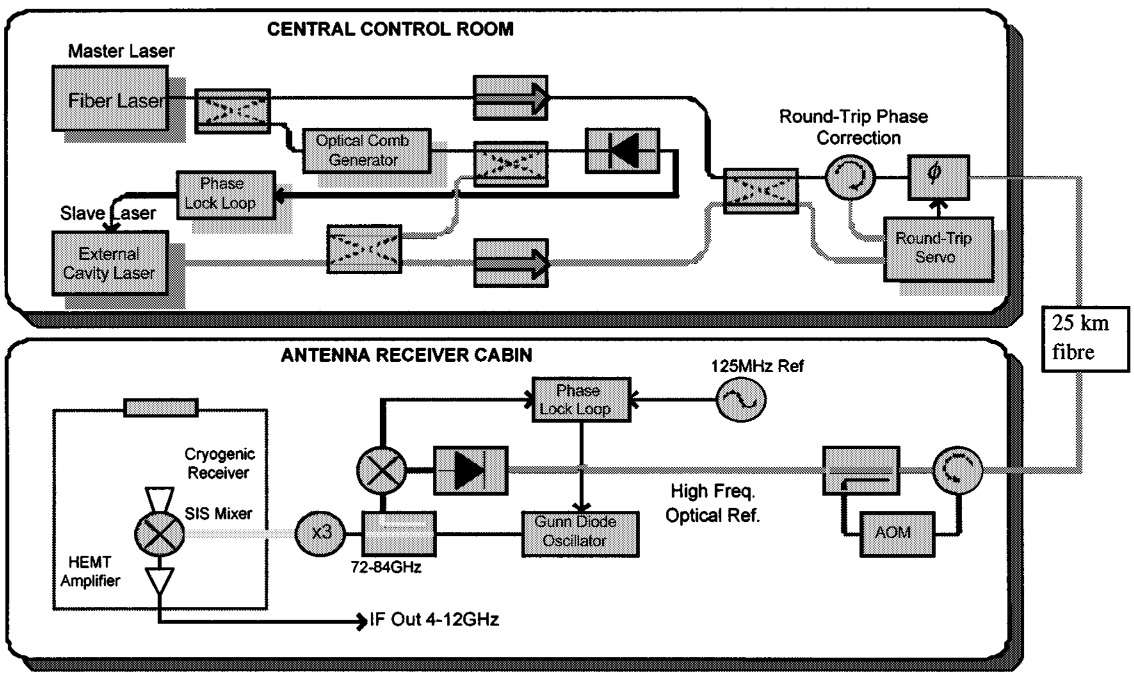



Fig. 9. Optical local-oscillator generation system for radio astronomy [courtesy of John Payne (National Radio Astronomy Observatory (NRA), Green Bank, WV)/Phil Davies (University of Kent, Kent, U.K.)].

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 broad-band networks with well-controlled noise performance to be constructed, and plays an important part in distribution networks for cable television. Fiber radio for cellular access has become a significant commercial market. With the drive to offer broad-band wireless access, it is very likely that the market share of fiber-radio access systems will grow further.

Now that the majority of fixed communication is by optical fiber, and per-channel data rates are rising through 40 Gb/s, the need for microwave photonic 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 [122] and these are becoming more attractive as the optical response of microwave devices has been improved [78]. 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 sub-millimeter-wave 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 beam forming and 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.

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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 author would, therefore, like to take this opportunity to thank his colleagues in academia and industry for their many contributions to advancing the field of microwave photonics whether their work has been specifically cited here or not.

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