RF Photonics

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Invited Paper

***Abstract*—In parallel with the development of fiber optics for transmission of digital information, the 1970s and 1980s saw the development of techniques for the transmission of wide-bandwidth analog radio-frequency (RF) signals over optical fibers. The simultaneous need for high linearity and high signal-to-noise in RF photonic links spurred the development of lasers, modulators and detectors matched to the special needs of such links. RF photonics was also explored for the processing of RF signals by means of optically implemented filters and variable-delay lines. Commercial applications of RF photonics included cable television signal distribution and subcarrier-multiplexed digital signals.**

***Index Terms*—Analog systems, antenna feeds, cable television (CATV), microwave communication, optical fiber communication, optical fiber delay lines, optical modulation, photodetectors, signal processing.**

I. Introduction

DURING the 1970s, interest in the use of fiber optics for communication grew rapidly. The technology for optical sources (especially diode lasers), low-loss fibers, and high-speed detectors advanced to the point where field trials and production of new systems occurred by the end of the decade. This interest was driven primarily by the prospect of revolutionary advances in the cost and range of systems for the transmission of digital information. However, there was much less interest in the use of fiber optics for the transmission of analog signals, an area which has subsequently been called microwave or radio-frequency (RF) photonics. This paper looks back at the thinking and technical state of the art concerning RF photonics in the early days of fiber optics. The focus is on advances made up to end of the 1980s, the decade in which the JOURNAL OF LIGHTWAVE TECHNOLOGY began publication. A review of the immense amount of research and development in RF photonics since that time is provided by several books [1], [2] and articles. The papers cited in this historical overview were all published up to 1990 and do not include the many significant technological advances and applications since that date. The list of references is only a sampling of the many advances made during the 1970s and 1980s.

Manuscript received February 19, 2008; revised March 13, 2008. The Lincoln Laboratory portion of this work was sponsored by the U.S. Air Force under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not endorsed by the U.S. Government.

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Digital Object Identifier 10.1109/JLT.2008.923627

Although the attractive features of optical fiber transmission (low loss, high bandwidth, etc.) appear well suited for transmission of analog signals, the detailed requirements for analog and digital transmission are quite different. Requirements for high signal-to-noise and high linearity led the RF photonics field to different approaches and components than used for transmission of digital signals [3].

Why would one want to transmit signals in analog form rather than just sending the digital information? In the 1980s, it was very difficult to convert analog information into bits with high fidelity (large number of effective bits) at high bandwidths (high sampling rate). Therefore analog transmission made sense. Even after several decades of development of analog-to-digital converters, digitizing wide-bandwidth signals remains difficult. In addition, the analog-to-digital converters add cost, power, complexity, and environmental constraints that argue against their use.

What types of systems can effectively utilize analog signal transmission? The most straightforward application is simple point-to-point transmission between an antenna and a central information processing system. A lot of attention has been paid to the use of fiber optics in phased-array antennas where there is intensive multiple-point transmission between a central processor and the antenna elements or subarrays. Analog fiber optics also showed promise of providing a crucial component in wide-bandwidth phased-array antennas, namely a wideband switchable delay. Telecommunications companies investigated the use of RF photonics for distribution of cable television (CATV) signals and for subcarrier multiplexing of digital signals onto an optical fiber. From the 1970s onward, researchers looked at some novel methods for processing of RF signals including the implementation of microwave filters that exploited the wideband delay provided by fiber optics.

II. Basic RF Photonic Transmission

Any use of RF photonics starts with the requirement that an analog signal must be transmitted from point to point with high fidelity. Can the cable shown in Fig. 1 be replaced by the fiber-based transmission? What advantages would the optical transmission system provide? What technology should be used for the input RF-to-optical EO converter and the output optical-to-RF converter?

In addition to the well-recognized features of low loss, low size, low weight, and large bandwidth, optical transmission of RF signals also provides immunity to electromagnetic interference and the ability to transmit RF signals at frequencies not readily accommodated in conventional cables.

The basic approach for transmission of digital information is to modulate the current into a semiconductor optical source and

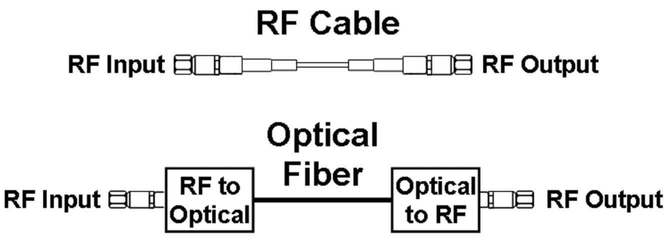

Fig. 1. Conventional RF cable and its replacement by an RF-photonic link that employs two critical elements, an RF-to-optical converter and an optical-to-RF converter.

thus modulate the optical power emitted into an optical fiber. In the 1970s, emphasis shifted from LED sources to diode lasers as the technology and performance of these devices rapidly advanced. In this case, the digital-to-optical converter is a diode laser and the optical-to-digital converter is a detector followed by an electrical amplifier. However, it was well recognized that higher signal-to-noise in the receiver could be achieved through the use of heterodyne detection thus extending the range of optical fiber transmission of digital information. There were many efforts to develop fiber transmission systems employing heterodyne detection [4], [5].

Following in the footsteps of the technology for digital transmission, RF photonics researchers looked at the tradeoffs between incoherent and coherent detection [6], [7]. Direct detection yields an output electrical voltage proportional to the optical power incident on a detector while coherent detection yields an output voltage that is linear in optical amplitude or phase. While the enhanced signal-to-noise of coherent transmission looked attractive, the overall performance and complexity of a coherent-transmission RF photonics link did not seem worthwhile, although there were several demonstrations of coherent systems for transmission of community antenna or CATV signals [8]. Unlike digital transmission systems, RF photonics requires high linearity. It is difficult to achieve the required linearity in devices used to modulate an RF signal onto an optical carrier and then demodulate the signal in a heterodyne receiver. With few exceptions, the RF photonics field had relied on incoherent transmission, i.e., intensity modulation.

Unlike digital transmission, RF photonics requires the transmission of fully analog signals that swing both positive and negative. Therefore, the RF signal must be placed on a dc bias. The RF-to-optical converter must emit a level of optical power P_0 when there is no RF signal. The RF signal is added to this power such that the deviation of the optical power from P_0 is proportional to the instantaneous amplitude (not power) of the RF signal. The optical-to-RF converter is an optical detector followed by an electrical amplifier. The amplitude of the signal out of the detector V_{OUT} is given by

$$V_{\mathrm{OUT}} = T\,R\,Z\,(P_0 + P_{\mathrm{RF}}) \qquad (1)$$

where T is the power transmission loss from the RF-to-optical converter to the detector and R is the responsivity of the detector and associated circuitry and Z is the load impedance on the detector.

Equation (1) is simple, but points directly to major considerations for RF photonics. Because V_{OUT} is proportional to T, every one decibel of optical loss results in 2 dB of reduction in output RF power. Therefore, low optical loss is vital. High detector responsivity R is also important. In order for the system to carry RF signals, the peak value of P_{RF} must be less than P_0. As will be discussed later in this paper, demand for high linearity usually requires that P_{RF} be much smaller than P_0. However, the peak value of P_{RF} must be large in order to achieve high signal-to-noise in the output. The net result is that the entire optical system must operate at substantially higher optical power levels than are typically required for transmission of digital signals.

As a result of the use of high optical power, the detector (optical-to-RF converter) must simultaneously provide high responsivity, high linearity, and high bandwidth. These combined requirements impose some difficult tradeoffs. High speed requires thin active regions while efficiency is enhanced with thick active regions. Nonlinearities arise at high optical powers. These conflicting requirements have pushed the development of specialized RF photonics detectors from the beginning, and efforts continue to this day [9], [10].

An RF photonics transmission system can be constrained by optical fiber nonlinearities at the high optical power levels. The power threshold for stimulated Brillouin scattering is proportional to L^{-1} where L is the transmission distance. An offsetting feature of RF photonics is that, unlike digital transmission systems, transmission over the longest possible distance is not the usual goal. For distances less than a kilometer, the threshold is 100 mW or more. The RF transmission distance in antenna systems typically ranges from tens of meters to a few kilometers so optical nonlinearities have a short distance over which to build. RF photonics for CATV and digital transmission systems employing subcarrier multiplexing do place more emphasis on long-distance transmission.

RF photonics systems operate within a finite passband around an RF carrier. The systems do not have to transmit dc signals. Therefore, a high-pass filter easily removes dc levels in (1). However, P_0 is never constant. There is always an intensity noise associated with optical power. Equation (1) must be modified to reflect this intensity noise

$$V_{\mathrm{OUT}} = T\,R\,Z((1 + \mathrm{RIN}^{1/2})P_{\mathrm{AVE}} + P_{\mathrm{RF}}) \qquad (2)$$

where RIN is the relative intensity noise in the RF passband as measured at the output of the detector. Therefore neglecting noise added in a postamplifier, the signal-to-noise (S/N) power at the output of the RF photonics transmission systems is

$$\mathrm{S/N} = (P_{\mathrm{RF}}/P_{\mathrm{AVE}})^2/\mathrm{RIN}. \qquad (3)$$

The fundamental limit on S/N is the shot noise associated with P_{AVE}. Because P_{RF} is usually much smaller than P_{AVE}, optical sources with very low RIN are required in order to yield high S/N.

Another important consideration is the effective noise figure at the input to the RF transmission system. Large RF-to-optical conversion loss results in a low noise figure. While an RF preamplifier at the input to the optical link can improve the noise figure, the overall noise figure is always worse than that of the preamplifier alone. If the conversion loss is large, an overall low noise figure requires rather heroic preamplifiers with low noise figures and high linearity at high RF output power.

The basic considerations reviewed in this section were recognized early in the development of RF photonics. These systems require high optical power, low loss, low RIN, high P_{RF}, sensitive RF-to-optical converters and detectors with high bandwidth and high responsivity while remaining linear at high optical power.

III. Dynamic Range

RF photonics places great stress on high dynamic range. RF photonic and digital transmission systems differ significantly in their requirements for linearity and signal-to-noise [3]. In transmission of digital signals, the key figure of merit is the bit error rate (BER), usually plotted as a function of received power or photons per bit. The eye diagram and the signal-to-noise determine the BER. Nonlinearities are inherent in the generation of digital signals. The BER decreases as a function of the power in the receiver and only at very high power levels does the BER rise as a function of received power. Typically a 20-dB ratio of peak signal-to-noise is adequate to provide an acceptable BER. In contrast, the performance of RF photonics systems is very sensitive to nonlinearities. A peak signal-to-noise of 60 dB or more in a wide bandwidth is often required. These combined requirements cause RF photonics systems to differ significantly from digital transmission systems.

The term "dynamic range" for analog systems is often confusing. Consideration of both the maximum and minimum signals is important in order to understand and specify dynamic range. In an RF-photonics system, the top end of the dynamic range is set by the maximum input signal that can be transmitted while generating a tolerable level of spurious signals. These are generated by nonlinearities in the transfer function. Spurious signals, not gain compression, are the primary limit on the top end of the dynamic range.

Two types of spurious signals usually dominate. Quadratic nonlinearities in the transfer function generate spurious signals at the second harmonics of the input signals. These harmonic signals must be minimized in RF-photonic systems that operate over more than an octave bandwidth ($f_{\mathrm{MAX}} = 2f_{\mathrm{MIN}}$, or 67% fractional bandwidth). Second-harmonic signals can easily be filtered out for systems with less than an octave bandwidth. The second type of spurious signal is that caused by cubic and higher-odd-order nonlinearities. Cubic nonlinearities generate spurious signals at the third harmonic of the input signal and also give rise to the most troublesome spurious signals, two-tone third-order intermodulation products. Input signals at f_1 and f_2 generate intermodulation products at $2f_1 - f_2$ and $2f_2 - f_1$. These spurious signals fall within the bandwidth of the system no matter how small the fractional bandwidth. Many RF systems demand spurious signals 60 to 90 dB or more below the primary signal and thus place stringent demands on linearity.

The bottom end of the dynamic range is set by the level of the input signal that will yield a minimum detectable signal, typically taken as S/N = 1, at the output. The dynamic range is the ratio of the maximum input signal (set by the maximum spurious signals) to this minimum signal. Any specification of dynamic range requires that both the level of the spurious signals and the noise bandwidth be specified. RF-photonics developers realized that consistent, well-defined, and widely accepted measures of dynamic range were needed. The conventional overall measures of performance are shown on a log-log plot such as in Fig. 2. The horizontal axis is the level of the input signal and the vertical axis is the level of the fundamental output, the second harmonic, the third-order intermodulation products and the noise in a specified bandwidth. Except at high input power levels, the fundamental output has a slope of one, the second harmonic has a slope of two, and the intermodulation products have a slope of three or higher.

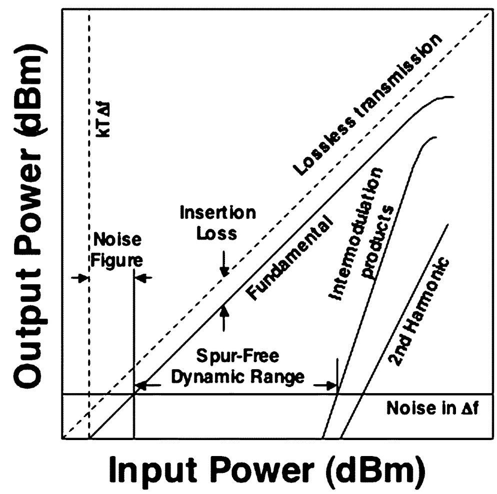

Fig. 2. Output versus input characteristics of an analog transmission systems illustrate the key features of insertion loss, spurious signal levels, noise, noise figure, and spur-free dynamic range.

One of the standard single-number measures of dynamic range is the "spur-free" dynamic range. This is the ratio of the maximum signal to the intermodulation spurs when these spurs are at the noise level. Because the noise power is proportional to noise bandwidth Δf, the spur-free dynamic range is proportional to the $\Delta f^{-2/3}$. The single number given for third-order intermodulation-dominated spur-free dynamic range is in units of dB $\cdot$ Hz$^{2/3}$. The RF photonics field learned early on that spur-free dynamic range of about 60 dB $\cdot$ Hz$^{2/3}$ could be readily achieved, but most systems demanded numbers of 100 dB $\cdot$ Hz$^{2/3}$ or more, levels not readily achieved without technological advances in lasers, modulators and detectors.

Second-harmonic spurs can be suppressed by operating a transmission system with a dc bias on the input adjusted for operation about the inflection point of the overall transfer function for the transmission system. However, suppression of second harmonic spurs by many tens of decibels requires precise tracking of the inflection point and setting of the bias to that point. For transmission systems operating at more than an octave bandwidth, spur-free dynamic ranges for both second harmonics and intermodulation products must be considered.

IV. Diode Lasers for RF Photonics

The most straightforward way to implement analog transmission systems was to capitalize on the rapid advances being made during the 1970s and 1980s in diode lasers for digital fiber transmission. The basic configuration for direct modulation of diode lasers is shown in Fig. 3. The relative linearity of the dc output power versus current suggested that a diode laser should be an excellent RF-to-digital converter. Both digital and RF photonics benefited from increases in power levels and bandwidths

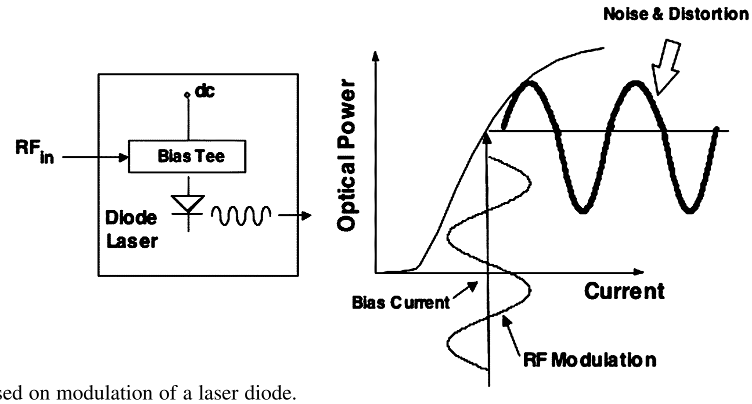

Fig. 3. RF-to-optical converter based on modulation of a laser diode.

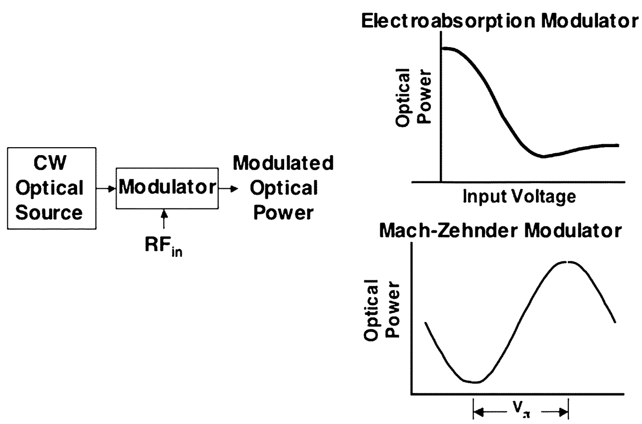

Fig. 4. RF-to-optical converter based on external modulation of a CW laser. Typical characteristics of two types of external modulators, an electroabsorption modulator and a Mach–Zehnder modulator, are shown.

of diode lasers [11]–[14]. Bandwidths kept increasing from fractions of a GHz to 10 GHz or more thus recommending diode lasers for transmission of analog microwave signals.

Many researchers examined the linearity of diode lasers both theoretically and experimentally [15]–[23]. While the dc power-current characteristics were often quite linear, it became evident that the level of nonlinearities and the resulting spurs were dependent on the frequency of the modulation relative to the relaxation-oscillation frequency of the laser. For reasonably linear response, the maximum RF frequency has to be well below the relaxation-oscillation frequency. This relationship imposes a tradeoff between bandwidth and spur levels.

Early diode lasers had little control over the lasing modes. The result was RIN far worse than the shot-noise limit. By the end of the 1980s, typical diode lasers had a RIN of about -130 dBc/Hz at emitted power levels of a few milliwatts. This is more than 30 dB worse than the shot-noise limit.

As (1) indicates, high-dynamic-range RF photonic systems must operate at high optical power levels. In a diode laser, the level of the modulation of the emitted optical power is intimately related to the input RF power level by the differential quantum efficiency. With good diode lasers of the era operating at about 10 mW, the maximum RF modulation was limited to similar levels. This fact combined with high RIN yielded limited signal-to-noise at the output of an RF-photonics link. The difficulty of efficiently matching an RF driver (typically 50 Ω) to the low impedance of a diode laser resulted in high conversion loss. Overall RF-to-RF loss was 10 to 30 dB. This feature combined with high RIN yielded poor noise figures (20 to 40 dB) for a diode-laser based RF-photonics system. Such systems had difficulty providing a spur-free dynamic range of > 100 dB/Hz$^{/3}$.

Another difficulty with diode lasers of the 1980s was the interplay between modal noise and dispersion. The optical spectrum out of a typical laser was far wider than the Fourier limited bandwidth due to amplitude modulation. As with digital transmission systems operating over long distances, RF-photonics systems were also degraded. High performance demanded narrow linewidths even under intense high-frequency modulation. These features were difficult to achieve and remain a challenge today, but mode control in DFB lasers has greatly advanced since 1990 [24], [25].

Despite the recognized limitations of diode lasers, RF-photonics systems employing these lasers were extensively developed and attractive capabilities were demonstrated, including an RF-photonic link from a remote antenna [26].

V. External Modulators for RF Photonics

For the most demanding RF-photonics applications, researchers focused their efforts on systems employing external modulators as shown in Fig. 4. The great advantage of external modulators is that the system can use continous-wave (CW) laser sources that operate at high powers with low relative intensity noise. Modulators that employ changes in index of refraction (electro-refractive or electro-optic modulators) include directional-coupler and Mach–Zehnder (MZ) modulators.

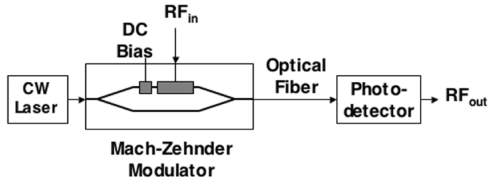

Fig. 5. RF-photonic link employing a Mach–Zehnder external modulator.

Research in guided-wave electroabsorption modulators for use in fiber optics started in the 1970s [27]. Development accelerated during the 1980s, driven by the desire for digital modulators in III-V materials that could be integrated with CW diode lasers. In parallel, electroabsorption modulators were developed and evaluated for use in RF photonics [28]–[31].

In the 1980s, two types of electro-optic modulators were developed for use as external modulators, directional-coupler modulators and MZ modulators. For the highest levels of performance, both types of modulators relied on the low-loss and high electro-optic coefficients of $LiNbO_3$. These non-absorptive devices can handle much higher optical powers (up to about 400 mW) than can electroabsorption modulators (limited to a few tens of milliwatts). Researchers at Bell Laboratories were the major developers of directional-coupler modulators [32]–[34]. Several researchers at Bell Laboratories and elsewhere looked at the tradeoffs between the two types of electro-optic modulators (e.g., [35]). A MZ interferometer/modulator is shown in Fig. 5. Demonstrations of guided-wave MZ modulators began in the 1970s [36]. The 1980s saw many advances in the technology for MZ modulators for both digital and analog applications [37]–[45].

One difficulty with MZ modulators for analog modulation is that their transfer function is sinusoidal (Fig. 4) and therefore linear over only a small modulation depth. In standard analog operation, the modulators are biased at the quadrature or half-power point so as to operate in this most linear region. The consequences of inherent modulator nonlinearity were analyzed in many papers (e.g., [46] and [47]). Schemes were explored for operating modulators in nonstandard ways so as to achieve greater linearity. Johnson and Roussell demonstrated an MZ modulator operated with two different polarizations so as to reduce intermodulation distortion [48]. Following this demonstration, other researchers showed that two interferometers operating in parallel could yield similar suppression of nonlinearities [49], [50]. Another approach is to employ electronic predistortion circuits at the input of an MZ modulator to compensate for nonlinearities [51]. In later work, many different configurations that yield suppressed nonlinearities were proposed and demonstrated.

Several researchers examined the tradeoffs between diode lasers and external modulators as electrical-to-optical converters in RF photonics [52], [53]. Despite their relative simplicity, diode lasers had the major limitation of high RIN levels. However, advances in DFB lasers have substantially reduced RIN levels.

The choice of operating wavelength for external-modulator RF-photonics involved several factors. The sensitivity (oscillating RF output power versus applied RF voltage) of an MZ modulator is a strong function of wavelength with shorter wavelengths yielding better response. A lot of early work examined MZ modulators at 0.85 μm, a wavelength where diode lasers were readily available [39], [54]. At this wavelength, deleterious photorefractive effects made long-term operation difficult [38]–[40]. The 1.06-μm wavelength of Nd:YAG lasers was also explored, but photorefractive effects still interfered. In contrast, photorefractive effects proved immeasurably small at 1.3 μm. The rapidly advancing range of components being developed for digital fiber-optic transmission pushed RF-photonics toward 1.3 μm. The highest-performance RF photonics systems with MZ modulators took advantage of the newly developed diode-pumped Nd:YAG lasers that operate on a line at 1.3 μm [51], [53]–[58]. These lasers provided 100 mW or more of nearly shot-noise limited ($\sim$ 160 dBc/Hz) power making the lasers an ideal source for high-fidelity RF photonic links. During the 1980s, the digital fiber optics field pushed toward 1.5 μm because of the lower transmission loss. However for modest-distance RF photonic analog links, the reduction in loss at 1.5 μm was usually insignificant and more than offset by the enhanced modulator performance at 1.3 μm.

The overall RF-to-RF power gain of an RF-photonic link is proportional to the square of the slope of the output power versus voltage of the external modulator. This slope is proportional to the power delivered by the CW laser P_L and to the slope of the transmission versus power of the modulator. For an MZ modulator

$$\text{RF-to-RF Gain} \sim (P_L/V_\pi)^2 \quad (4)$$

where V_π is the voltage that changes the phase shift in the two arms of an MZ interferometer by 180° and therefore swings the transmission from a minimum to a maximum. Equation (4) shows that high power and high sensitivity (low V_π) are keys to RF-photonic links with low noise figure and high dynamic range. Since the early 1980s, researchers have spent a great deal of effort on obtaining lower values of V_π in MZ modulators with values of V_π declining from tens of volts to a few volts over the years.

The first low-frequency $LiNbO_3$ MZ modulators were treated as lumped-element devices with the drive voltage applied to the electrode capacitance. However, researchers realized that the highest frequency response would be achieved in MZ modulators driven as traveling-wave transmission lines with characteristic impedance close to 50 Ω [33], [35], [37], [42], [43], [45]. For bandwidths below about 1 GHz, resonant drive of the capacitance allowed low effective V_π values to be obtained over a limited bandpass [43]. An RF-photonic link with a high-power laser and a resonant drive of an MZ modulator demonstrated that a very low effective V_π and a net RF-to-RF gain of 11 dB could be achieved [44]. The net result was such a low noise figure that links of this type were used in an antenna array that required no preamplifiers. The individual antenna elements were resonantly matched to MZ modulators. Careful attention to matching circuits demonstrated that an RF-photonic link with gain could be achieved at L-band [57].

VI. Applications of RF Photonics

Early in the history of fiber optics Henry Taylor examined the implications of this rapidly growing technology, especially for military applications [59] including links to antennas, delay lines, filters, and several signal processing functions. Subsequently during the 1980s, RF photonics for military applications

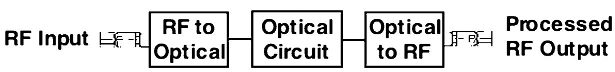

Fig. 6. RF-photonic system with an optical circuit for processing the RF signals.

were investigated at many laboratories with major efforts at the Naval Laboratory in San Diego, the Naval Research Laboratory, Hughes Research Laboratory and MIT Lincoln Laboratory.

The most obvious application of RF photonics was to replace bulky and lossy metallic cabling in radar and communications antenna systems. In conventional systems with cables and waveguides, all wideband elements of a system have to be located close to each other to minimize the impact of RF losses. The low loss of fiber optics means that, for distances out to several hundred meters, the performance of a system employing RF photonics is nearly independent of the distance between the various components. This general area of endeavor is often referred to as "antenna remoting." During the 1980s, several laboratories demonstrated RF-photonic links operating at RF frequencies up to 20 GHz with attractive characteristics [26], [51], [55]–[57], [60]. RF-photonic links appeared attractive as a small-size high-bandwidth means of communication between a central processor and the many antenna elements in a phased-array antenna [55]. The group at Hughes Research Laboratories demonstrated that a RF-photonic link was useful as a broadband delay element for testing and calibration of radars [62]. In another novel application of RF-photonics, an MZ modulator coupled to a small antenna element proved useful as a broadband nonperturbing probe of RF fields [63]. Analog fiber-optic links were evaluated for the transmission of high-speed transient signals from a remote location [58], [64].

The promise of long delays at high bandwidths stimulated a number of researchers to examine a broad range of applications of RF photonics beyond straightforward point-to-point links. What could be done if an optical circuit were placed within a RF-photonic link as shown in Fig. 6? Prospective uses included filtering, radar beam forming, and variable-delay lines [59], [65]–[70]. A prerequisite for any such application is the requirement that a simple point-to-point RF-photonic link operate with adequate dynamic range. The demonstration of such a capability during the 1980s opened the door for more complex signal-processing applications.

Phased-array antennas are used in many situations because these antennas provided rapid electronically steerable beams. In conventional phased-array antennas, a phase shifter for each antenna element adjusts the phase in order to steer the beam in a specified direction. However, the direction is unique to one particular frequency at any given setting of the phases of the array elements. As a result, a wide-band phased-array radar operating over several frequencies "squints," i.e., each frequency is peaked at a different angle in the beam. The problem becomes more severe for increasing angles off broadside. In order to eliminate beam squint, the phase shifter at each antenna element needs to be replaced by a broadband variable "true" time delay. This requirement spawned a lot of development of RF-photonic switched and continuously variable delay lines after 1990. A group at Stanford University demonstrated one of the first variable RF-photonic delay lines [71].

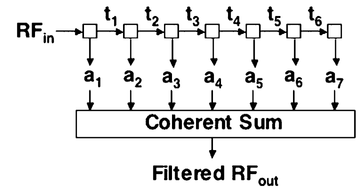

Fig. 7. Schematic diagram of a seven-tap tapped-delay-line or transversal filter. The input RF signal undergoes delays of t_1 through t_6 between the taps. The tapped signals are weighted by a_1 through a_7 and coherently summed to yield the filtered output.

Another class of applications of the structure shown in Fig. 6 is RF and microwave filters. An optical circuit consisting of an MZ interferometer with unequal delays in the two arms will provide an overall RF-to-RF response that has nulls at certain frequencies. If the optical circuit is a recirculating delay line, frequency nulls will also be obtained. The prospect of obtaining a filter with precise frequency nulls within a wide bandwidth spawned a number of efforts around the world after 1990. The group at Stanford University demonstrated one of the first RF photonic filters with frequency nulls [72], [73].

During the 1970s, there was increasing interest in filters with the configuration shown in Fig. 7. These filters are referred to as finite-impulse-response filters, nonrecursive filters, tapped-delay-lines filters, and matched filters. Fig. 7 illustrates a filter with seven taps. The time delays between taps are t_1 through t_6. The frequency response of a tapped-delay-line filter is given by

$$h(\omega) = \Sigma a_n \exp(i\omega T_n) \qquad (5)$$

where a_n is the weight of the nth tap and T_n is the cumulative delay to the nth tap.

The theory for designing and optimizing digital nonrecursive filters for sampled data became well developed and applied to the rapidly growing field of digital signal processing. During the 1970s, compact analog surface-acoustic-wave (SAW) devices underwent rapid advancement and application in many systems. SAW devices are tapped-delay-line filters that employ electrodes on a piezoelectric crystal surface to tap a propagating acoustic wave. Rapidly increasing acoustic losses at high frequency limit the operation of most SAW devices to below 1 GHz with bandwidths a fraction of that. The low loss and high bandwidth of optical fibers promised a means to implement tapped-delay-line filters at much higher frequencies and bandwidths. However, it became apparent that fiber optics would not be practical for implementing a microwave filter with the type of response shown in (4). The longest delays in a filter must be several times Δf^{-1} where Δf is the filter bandwidth. Obtaining good filter response requires that the delays be set to a few percent or better of a period of the propagating wave, i.e., a few percent of the wavelength of light. For Δf of the order of a GHz, the requirements for the stability of the delays and the laser frequency are daunting. The solution was to build tapped-delay-line filters that operate with incoherent light and use taps to sample the power (not the amplitude) in the propagating light. The tapped powers are incoherently summed. The Stanford group that had done much of the pioneering work in SAW devices was among the first to demonstrate a fiber-optic tapped-delay-line filter. In this case, light was tapped by microbends in a fiber [73], [74]. A matched delay filter was developed to perform direction finding in a RF receiver array

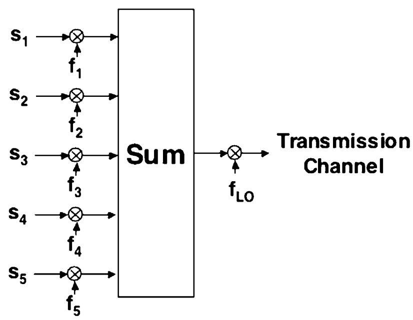

Fig. 8. Subcarrier multiplexing as used for transmission of both digital and CATV signals. The individual signals modulated onto lower-frequency carriers and the entire band of signals is mixed up to a higher frequency by means of the right-hand mixer. Bandpass filters to select the desired band at the output of each mixer are not shown.

[75]. Reflective taps placed in the core of an optical fiber were used to make a tapped-delay-line filter [76]. After 1990, a number of groups demonstrated tapped-delay-line filters that use fiber Bragg gratings spaced along a fiber as reflective taps.

VII. CATV and Subcarrier Multiplexing

During the 1970s, several laboratories began looking at the prospect that copper cables could be replaced by optical fibers for distribution of analog CATV signals [77]–[80]. The basic configuration for CATV transmission is illustrated in Fig. 8. Signals for separate channels s_1 through s_N are mixed with frequencies f_1 through f_N to generate N parallel signals on RF carriers that are then summed and transmitted over a cable. RF filters to select the desired mixer sidebands are not shown in Fig. 8. The technique is straightforward frequency-division multiplexing.

Nonlinearities in the transmission system will generate second harmonics and intermodulation products that degrade the signals in the individual channels. Instead of measures like spur-free dynamic range, the CATV industry uses the terms composite second order (CSO) and composite triple beat (CTB) to describe the relative level of the interfering spurious signals generated by quadratic and cubic nonlinearities, respectively. As the number of parallel channels increases, the transmission system must operate at higher power levels in order to provide adequate signal-to-noise in each channel. At the same time, more channels yield a higher level of CSO and CTB. Therefore, the challenge in CATV is to provide acceptable CSO, CTB, and signal-to-noise while carrying the maximum number of channels.

In some situations such as communication with a satellite, the summed signals in an RF band are mixed up to a higher frequency (usually microwave) carrier in a mixer as shown on the right of Fig. 8. The filter that selects the desired mixer sideband is not shown. Translation of a number of parallel channels onto a high-frequency carrier is known as subcarrier multiplexing. Fiber-optic subcarrier multiplexing is the process of placing the summed RF signals onto an optical carrier. Instead of a conventional mixer as shown in Fig. 8, a RF-to-optical converter is used. Its output is an intensity modulated optical wave, i.e., a RF-photonic link.

Subcarrier multiplexing was also developed for the transmission of digital signals. Individual digital streams are modulated onto a number of different carrier frequencies in the manner shown in Fig. 8. The sum of all of the signals is no longer binary, but rather is an analog signal that must be transmitted with high fidelity. An obvious extension of subcarrier multiplexing is mixed analog and digital transmission.

In the 1970s, fiber-optic CATV links based on LEDs were explored. With the rapid advances in diode lasers, attention shifted to systems based on these devices because of their wider bandwidth and higher powers. This shift focused attention on the bandwidth [12]–[14] and linearity [15]–[22], [81] of the lasers. Fiber-optic CATV systems advanced from transmitting 26 channels in 1979 [82] to 60 channels in 1987 [83] and 80 channels in 1990 [84]. During the 1980s, two of the major efforts in subcarrier multiplexing of CATV and digital signals took place at Bell Laboratories [19], [26], [52], [85], [86] and GTE Laboratories [8], [51], [83], [87]. A number of developers looked at the optimum mix of conventional copper cable and fiber-optics in CATV systems (e.g., [88]). Transmission of mixed microwave and digital signals over fibers was examined for as a means of communicating with the many elements of a phased-array radar [89].

VIII. Conclusion

Concepts and technological developments during the 1970s and 1980s laid the ground work for the considerable advancements in RF photonics since those beginning days. Continual development of lasers, modulators and photodetectors specialized for use in RF photonics has allowed the capability of the systems to improve to attractive levels of performance with high signal-to-noise, high bandwidth, and high dynamic range. Special optical circuits have implemented special signal processing functions including filtering and variable time delay. Applications of RF photonics have included single-aperture radars, antenna remoting, phased-array radars, RF field sensing, CATV signal distribution, and subcarrier multiplexing of digital signals.

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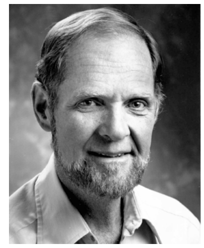

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