OPTICAL PROCESSING OF MICROWAVE SIGNALS FOR SMALL SATELLITE PAYLOADS

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ABSTRACT

For low altitude small satellite applications performing electronic surveillance or communication transponding missions highly capaple payloads are needed. Generally these spacecraft have low dwell times over the areas of interest and must receive, or search for, signals over a wide frequency band. This paper presents an approach to the implementation of optical processing in complex electronic systems intended to receive and operate on multiple radio frequency (or microwave) signals. The goal is to exploit the rapidly expanding field of linear and nonlinear optics to synthesize transponders and receiving systems for satellites and other platforms. The inputs are assumed to be microwave. The outputs are assumed to be microwave or electronic (digital). In between, the signal operations are performed optically. The focus of the effort is in the architecture for the electronic functions, that allow optical component realization. These elements perform the signal processing operations of: pulse signal detection and pulse parameter estimation; modulation and demodulation of AM, PM, and FM carriers; phase locked loop signal tracking; carrier element mixing (frequency shifting); signal filtering; and signal matched filter detection.

The spatial optical processing of ordinary time waveform signals offers significant potential benefits. It inherently provides wide bandwidth, high carrier frequency, and fast response processing capability. A signal Fourier transform can be performed with a simple lens. The second spatial dimension for parallel processing enhances the capability for exhaustive search of a signal space for parameters of interest. The two-dimensional optical implementation of switching and routing matches the channelized nature of many current communication systems. Increased optical implementations of electronic systems can take advantage of the rapid technological growth in applications and devices in this parallel discipline of optics to effect greater capabilities for the 1990's.

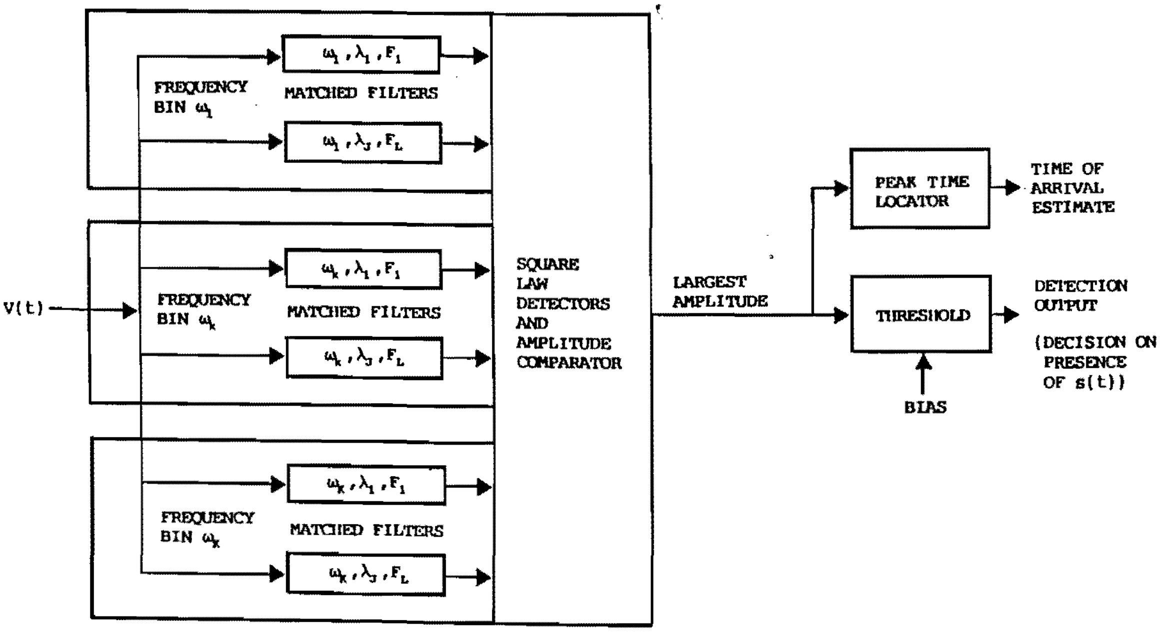
1. APPLICATIONS

In a spacecraft, airplane, ship, or other platform, particularly those performing a communication or radar function, a large number of electronic signals are received or transmitted. Many of these signals are very broadband and/or complex, resulting in large amounts of hardware to operate on or generate the waveforms present. Spatial optical processing, utilizing the inherent parallel processing, miniaturization, and wide bandwidth capability of optics, can substantially reduce the size, weight, and power of the equipment performing the electronic operations through embedded photonic crystals (the optoelectronic equivalent of the microelectronic chips). One notable system example is the exhaustive search over parameter space (frequency band, angle of arrival, spread spectrum codes, etc.) for specific signals of interest. Implementation in integrated photonics should allow an electronics subsystem of tremendoous capability in a simple surveillance platform such as a small low altitude satellite.

To realize the full benefits of photonics in communication systems will require all the necessary signal operations to be implemented in optical form. In addition to the typical linear operations of correlation, convolution, and filtering; the technology of which is well known; this entails the optical realization of such nonlinear operations as modulation, demodulation, and frequency shifting. An approach to accomplishing these functions on signal waveforms, employing modern techniques of nonlinear optics such as holography, phase conjugation, and frequency differencing, is indicated in Reference (1). The overall goal of this research program is to refine and expand this effort and to progress into laboratory demonstrations, simulations, and photonic crystal realizations to effect a proof of concept for these communication system ideas.

The communication theory embodiments and the modern optical technologies exist and are progressing rapidly. The contribution of this activity is to pull these disciplines together in a system context. This will provide the potential for new hardware implementations with substantially improved overall performance for heavily constrained electronic systems.

Figure 1 depicts an algorithm for maximum likelihood detection of microwave pulse signals (radar



ω_k = radian carrier center frequency of k^{th} filter bin

λ_j = pulse width of j^{th} matched filter function

F_ℓ = PRF (pulse repetition frequency) of ℓ^{th} matched filter function

Figure 1: Electronic Implementation of Optimal Radar Pulse Processor

signals) in which the pulse parameters; amplitude, frequency, phase, pulse width, pulse repetition frequency (PRF), and time of arrival; are all unknown. With this implementation the pulses are optimally detected and the unknown parameters are estimated. The detection structure is a bank of matched filters for the range of frequencies, PRF's, and pulse widths expected, followed by square law envelope detection and peak comparison. The output of the filter with maximum value provides the amplitude estimate, which is compared to a threshold to accomplish maximum likelihood detection of the desired signal.

The test statistic for radar pulse detection amounts to trying all possible frequency, PRF, and pulse width combinations, and locating the most probable by finding the peak output of a set of matched filters followed by noncoherent (square law) detectors. By locating relative peaks this receiver can be used for multiple pulsed (radar) signals. Clearly, this is a receiving system which heavily utilizes parallel processing and will benefit greatly from an optical implementation, which is shown in Figure 2. This is a linear system except for the intensity response of the photodetector array, which effects the desired noncoherent envelope detection. Under the assumption of pure amplitude modulation of the microwave carriers by the pulse waveforms, the acousto-optic spatial light modulator can be a Bragg cell, providing a single spatial sideband modulation function. This is a spectrum analyzer which separates the input into frequency bins. The matched filters are implemented in the Fourier plane, requiring a hologram to provide

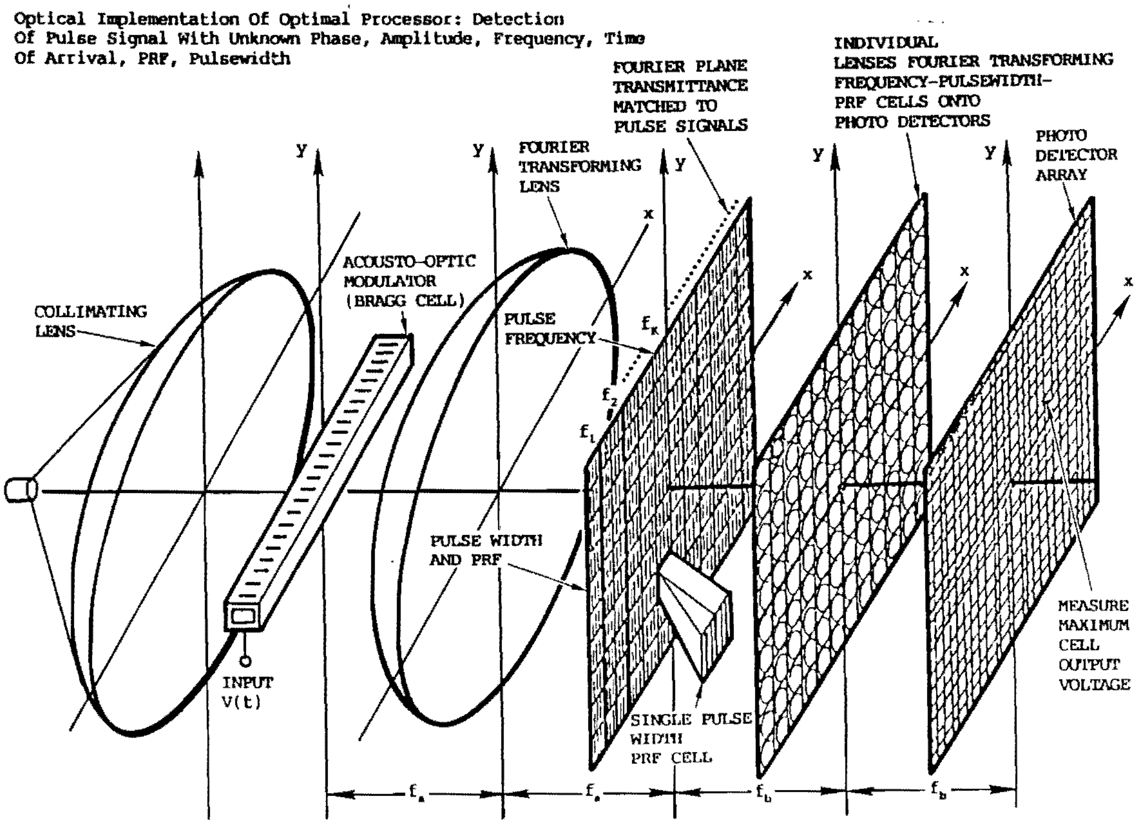


Figure 2: Optical Implementation of Optimal Pulse Signal Processor.

the phase function as well as the amplitude response. The illumination of the Fourier plane is uniform in the y dimension (Fourier Transform of $\partial(y)$), allowing parallel processing of the signal with a multituide of matched filters. The outputs of these filters are inverse Fourier transformed, on an individual basis, and then square law detected by the array. The peak outputs of the photodetectors represent a determination of the main parameters (frequency, PRF, and pulse width) of any pulse signals present. The accuracy of these estimates, subject to the resolution limits of the A-0 modulator, are determined by the number of distinct frequency bin/matched filter cells utilized. This could be thousands of cells, provided the design could achieve sufficient accuracy of beam deflection and quality in the optics. A single Fourier plane cell is shown as the exploded element of Figure 2 and the single cell processing operation of Figure 3. If the signal being detected is modulated in pulse width, PRF, and/or frequency (frequency hopped), the variations can be tracked as movement throughout the photo detector array.

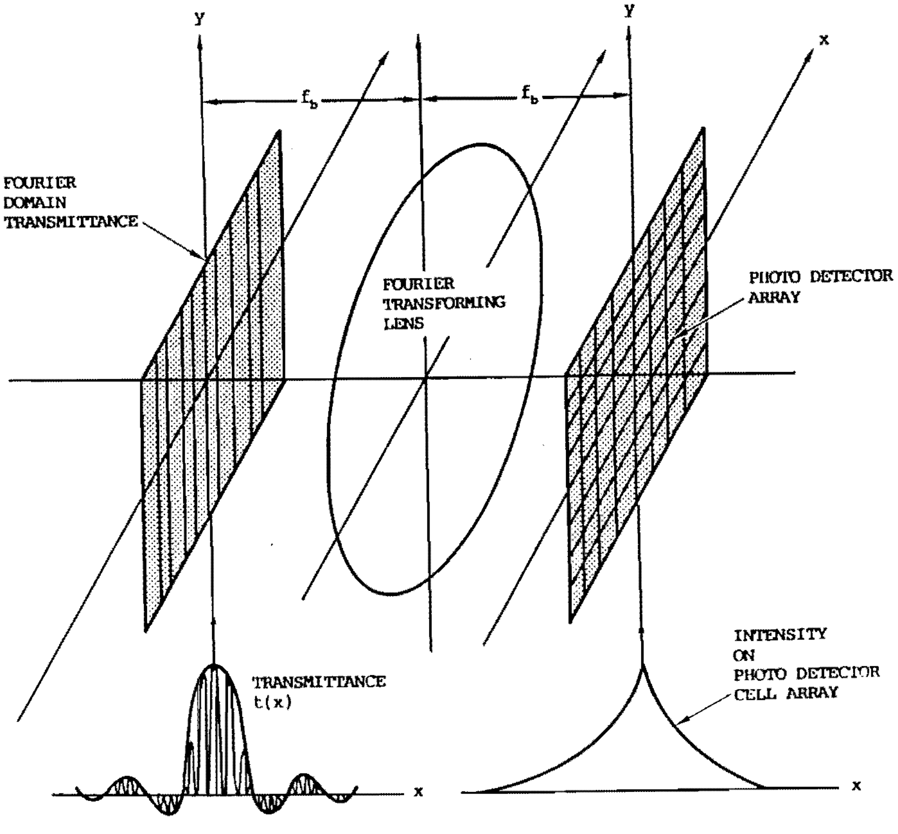


Figure 3: Matched Filter for Single Frequency/PRF/Pulsewidth Cell

A block diagram of a communications satellite transponder is shown in Figure 4, with the candidate portion for optical implementation bracketed. In this system considerable parallelism is present, and the hardware employed is greatly constrained by size, weight, power, and required reliability. It receives from a number of antenna beams and transmits over another set of antenna beams. The beam outputs are channelized by a set of microwave filters to separate the various received communication carriers (typically from different earth stations or users). The individual microwave carriers are then routed to various portions of the transponder for processing operations, presumably demodulation of the carriers and demultiplexing of the modulation into separate baseband channels, based upon the destination of the information. A second routing by a switch matrix is then required, followed by a multiplexing of channels to form a composite modulation signal for the downlink microwave carrier.

The inputs and outputs of the transponder are microwave; the processing required is assumed to be done optically without conversion back to microwave or video. The major goal is to convert the microwave signal to a spatial modulation on an optical beam, and to effect the processing architectures and devices required for amplitude, frequency, or phase modulation (and demodulation) of the microwave carriers, while they are modulated on the optical carrier.

Figures 5 and 6 depict a proposed optical processor implementation of this microwave transponder. An array of acousto-optic cells and the appropriate Fourier transforming and imaging lens will provide a multiple receiver channelization capability. The optical switching and routing is straightforward, possibly by holographic techniques, for both the microwave and video signals. Also shown are the phase and frequency demodulation and modulation processes, which are nonlinear operations on the information modulated onto the optical carriers.

2. MICROWAVE CONVERSION TO OPTICAL SPATIAL MODULATION

The input to the optical processor is a time varying received waveform v(t) (e.g. the output of a microwave preamplifier covering a particular frequency band). The spatial light modulator converts this input to a transverse spatial variation of an optical disturbance amplitude (such as the electric field amplitude of a coherent plane wave optical beam) as is shown in Figure 7. This output of the modulator can be represented by the amplitude function:

$$B_0(x,y,z,t) = \mathrm{Re}\{A_0\partial(y)\mathrm{rect}(\frac{x}{W})[1 + m_v v(t - \frac{x}{s})]\exp[-(j2\pi\nu t + j\o(x,y,z))]\} \qquad (1)$$

where m_v = modulation index constant of modulator, A_0 = amplitude constant of modulator, ν = optical carrier frequency, $\partial(y)$ = delta function of spatial variable y, $\o(x,y,z)$ = phase of optical carrier, rect = rectangle function, and W = width of aperture in x dimension. $B_0(x,y,z,t)$ represents the instantaneous field amplitude at the point (x,y,z) and at time t. It is depicted in Figure 8. v(t) is propagating in the x direction with velocity s. The entire optical amplitude is propagating in the z direction with propagation constant k. The modulation format of Eq. (1) is double sideband amplitude modulation (AM) in the spatial

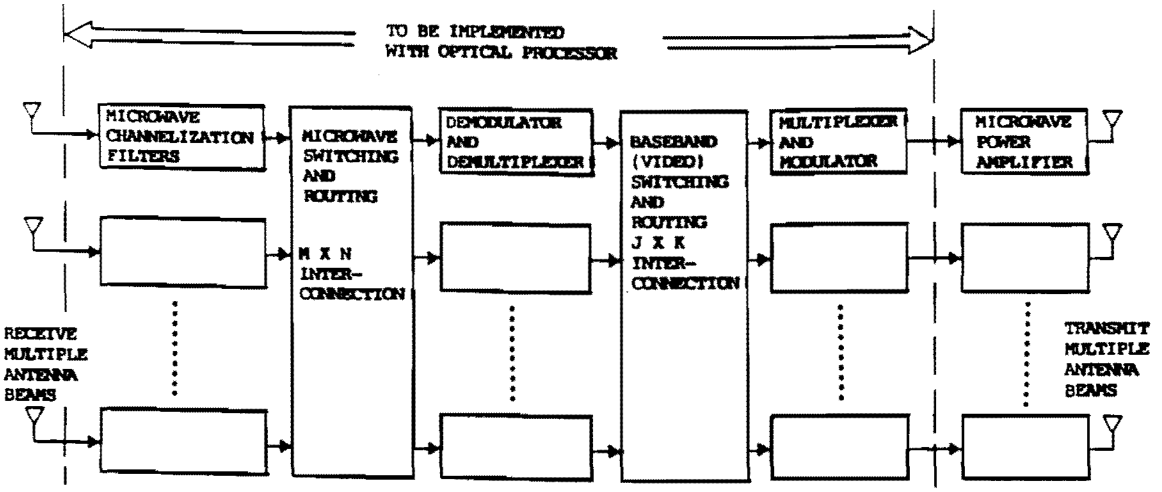


Figure 4. Demodulation/Remodulation Satellite Microwave Transponder

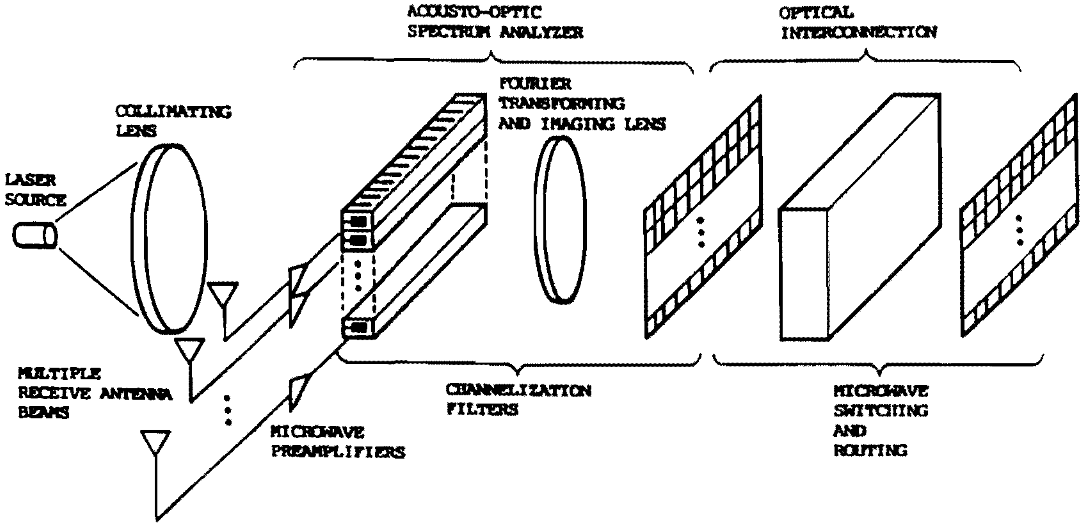


Figure 5. Optical implementation of satellite microwave transponder (part a)

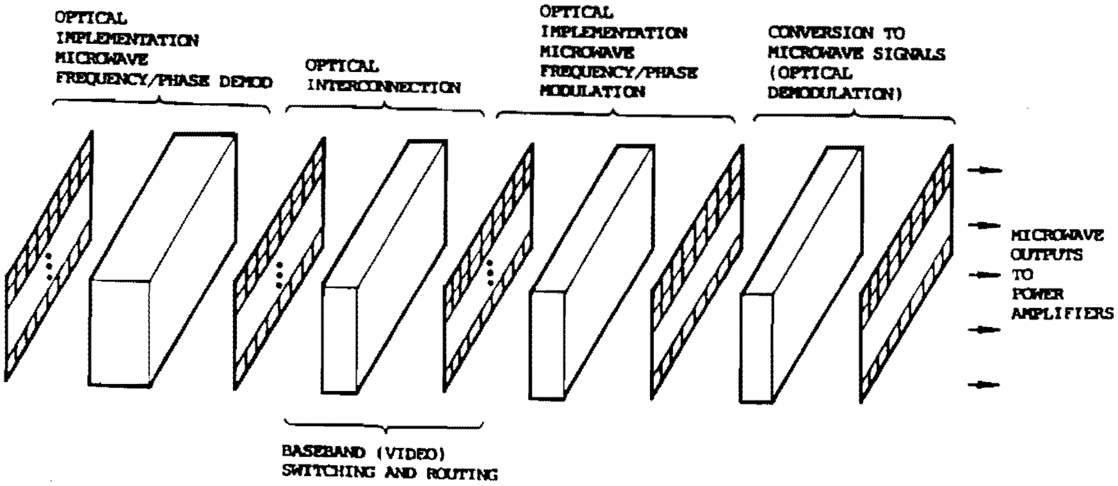


Figure 6. Optical implementation of satellite microwave transponder (part b)

domain. The further assumption, that $m_v v(t-x/s) < 1$, prevents overmodulation, normally expressed as having a modulation index less than 100%.This means that half of more of the optical power is in the spatial carrier component and the modulation can be recovered through a squaring operation, which can be accomplished with an intensity sensitive device.

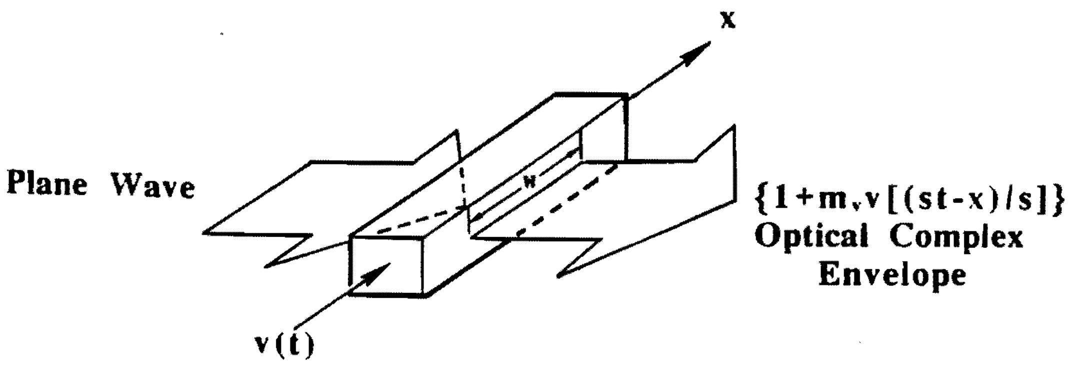


Figure 7. Hypothetical spatial light modulator

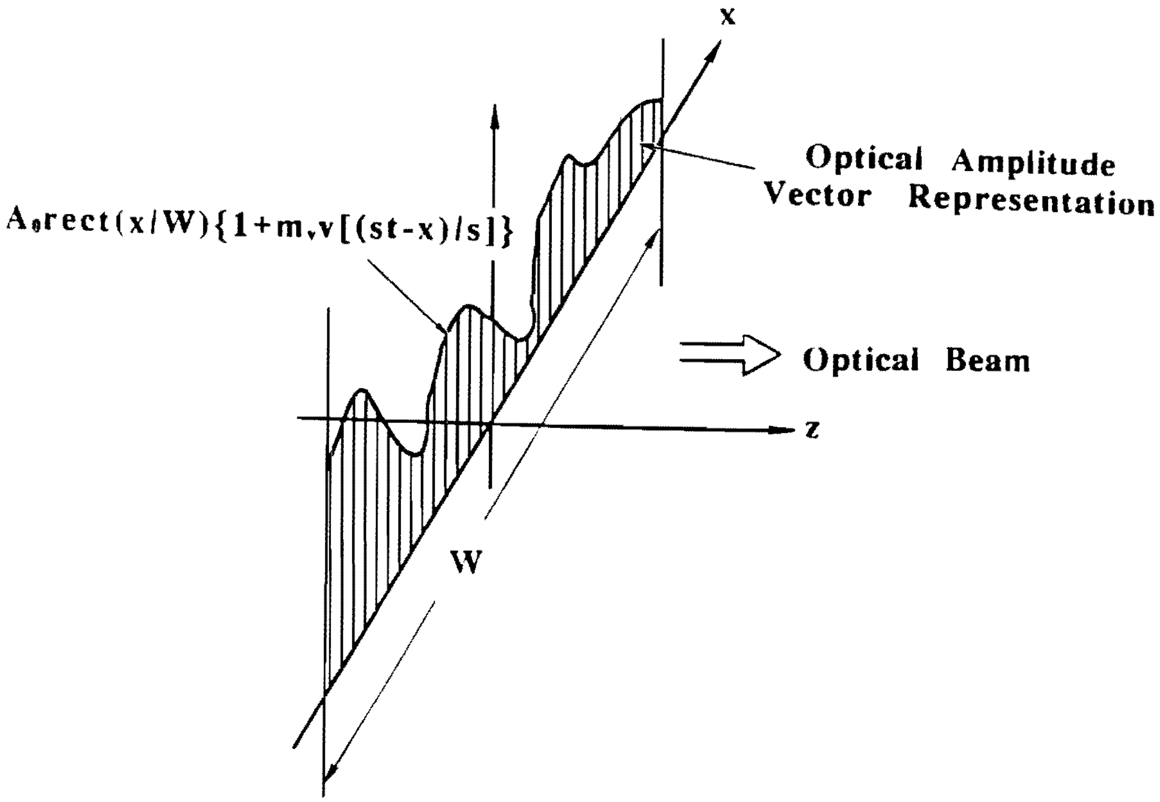


Figure 8. Signal v(t) converted to optical spatial variation

The aperture limitation (width=W) represents the portion of the input waveform being processed or operated on by the optical processor. This corresponds to the time observation interval [-T/2,T/2] of the conventional time domain detection and estimation problem. The width of the optical observation aperture, $W=sT$, and the propagation velocity s determine the width of the observation time interval, i.e., the amount of the input being instantaneously processed by the optical system. This is the reason acoustic spatial light modulators are attractive. Sound (pressure) waves in crystals propagate relatively slow ($\sim 10^4$ meters/sec) compared to the velocity of light (3×10^8 meters/sec). Thus, in an acousto-optic modulator the microwave signal is introduced as a pressure (sound) wave in a crystal in order to slow down the signal propagation and to modify the refractive index of the crystal, thereby modulating the optical beam.

The spatial waveform of Eq. (1) and Figure 8 can be considered to be an interference pattern in the x-y plane. From this point of view it is a time varying interference pattern that propagates along the x-axis, with the aperture limit (width = W) determining the amount of this pattern that the optical system system sees at any instant in time. The complex vector (or complex envelope) representation of the optical carrier in Equation (1) is useful in the optical processing operations and is consistent with the approach of Goodman.[2] The optical complex envelope is thus:

$$\underline{U}(x,y,z) = A_0\partial(y)\mathrm{rect}\left(\frac{x}{W}\right)\left[1 + m_v v\left(t - \frac{x}{s}\right)\right]\exp[-j\phi(x,y,z)] \tag{2}$$

In this analysis is is assumed that the basic coherency of the laser beam is maintained and that the relative phase among optical beams derived from the same source is identical (within factors of 2π in the optical phase). Therefore, the phase term in the complex envelope, $\exp[-j\phi(x,y,z)]$, is de-emphasized, resulting in a real complex envelope for all optical waveforms, since $v(t)$ is real. Operations are then performed on these complex envelopes to effect the desired optical processing.

3. OPTICAL SIGNAL CONVERSION BACK TO MICROWAVE

Another important consideration is the optical detection or demodulation function, i.e., the conversion from optical beam variations back to an electrical signal. The form of optical beam manipulations need to be consistent with conversion ease and efficiency of the optical detector implementation. Fundamentally, all optical detection devices operate by responding with an electrical output with amplitude proportional to the total optical intensity incident on the detection surface. For many of the applications envisioned it is desirable to detect the amplitude of the optical carrier in generating the electrical signal. This is a factor in the utilization of double sideband (spatial) modulation of the optical carrier. This same effect can be achieved by summing in a second carrier at the photodetector plane prior to intensity detection.

The output sensor is assumed to be a linear array of optical detectors along the x-axis where $\partial(y) = 1$. For an input of the form of Equation (1), the intensity along this line is given by:

$$\begin{aligned} I &= k_i \operatorname{rect}(\frac{x}{W})\, A_0{}^2 \,[1 + m_v v(t - \frac{x}{s})]^2 \\ &\approx k_i \operatorname{rect}(\frac{x}{W})\, A_0{}^2 \,[1 + 2m_v v(t - \frac{x}{s})] \end{aligned} \tag{3}$$

k_i = Intensity constant

The electrical (microwave) output at $x = x_0$ can be written:

$$\begin{aligned} v_0(t) &= 2m_v k_i\, A_0{}^2\, v(t - \frac{x_0}{s}) \\ &= k_0 v(t - \frac{x_0}{s}) \end{aligned} \tag{4}$$

$k_0 = 2m_v k_i\, A_0{}^2$ = constant

Therefore, the output is the desired form v(t) delayed in time by an amount x_0/s.

4. DEMODULATION OF MICROWAVE FM CARRIER

Although a general analytical approach has been developed for operating on microwave carriers as is described herein, two examples can best illustrate the techniques involved. First, an RF carrier frequency modulated by a frequency division multiplex of channels (e.g. voice or data circuits) will be demodulated and demultiplexed utililizing an optical processor. A widely employed electronic method of FM detection, the Foster-Seeley discriminator, is illustrated in Figure 9. Here the FM signal is converted to an AM signal and then detected as a conventional AM carrier. The first operation, FM/AM conversion, is accomplished by slope detection, a filter characteristic where amplitude response varies linearly with frequency (e.g. the skirt of a filter). The second operation of AM detection can be coherent or noncoherent envelope detection of a modulated carrier.

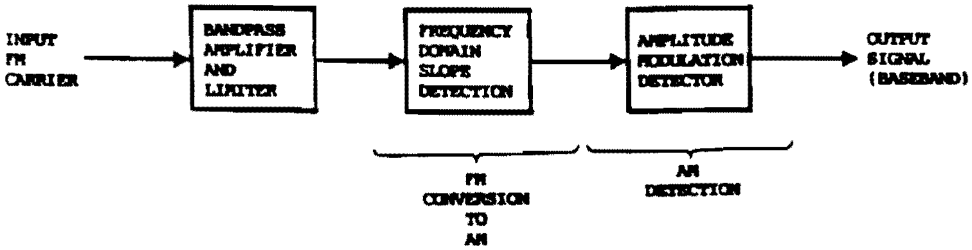


Figure 9 Electronic implementation of Foster-Seeley discriminator.

The optical equivalent to this FM discrimator is depicted in Figure 10. The slope detection is implemented in the Fourier domain by a transparency with a linear variation of transmittance across the spatial frequency band of interest, where the modulated carrier signal components are located. Here the optical signal must be Fourier transformed, passed through the transparency, and then inverse transformed to provide the appropriate signal for the AM detection. Because of the double sideband nature of the acousto-optic modulation, the slope function must be provided on both sides of the spatial carrier.

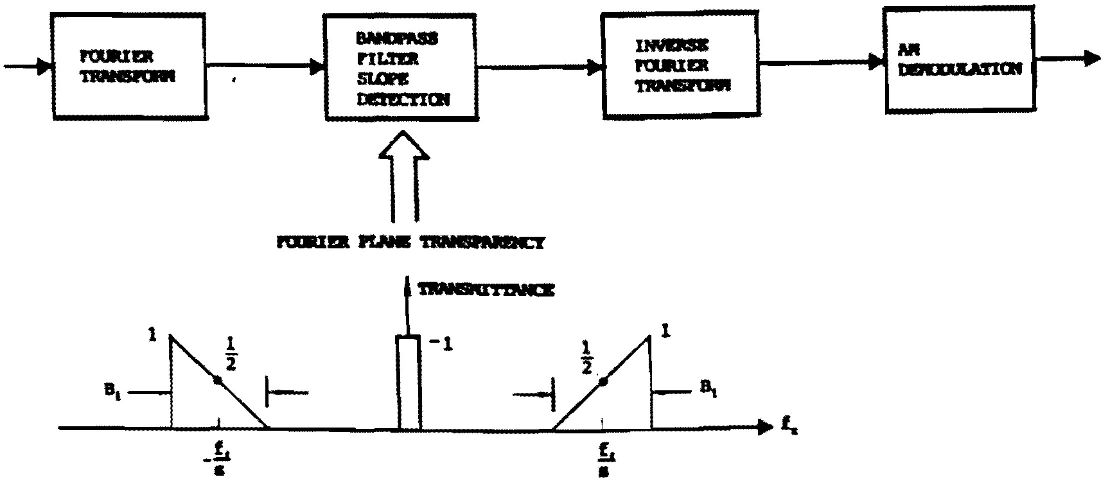


Figure 10. Optical implementation of FM discriminator.

The optical component realization of this demodulator is represented in Figure 11, where the types of devices and operations performed are emphasized. The FDM/FM microwave carrier is the acoustic input to the acousto-optic modulator, which is illuminated from the collimated beam formed from the single laser source. The lens elements perform Fourier transforms for purposes of transitioning to and from the spatial frequency domain. The essential element of the AM demodulator is an optical device with a third order

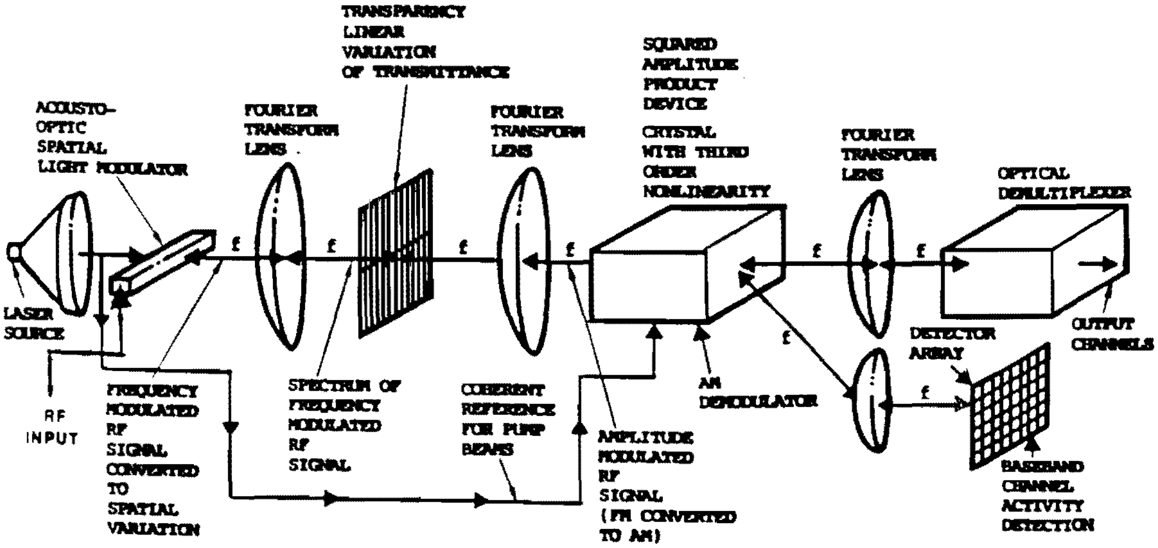


Figure 11. Optical component realization of FM discriminator.

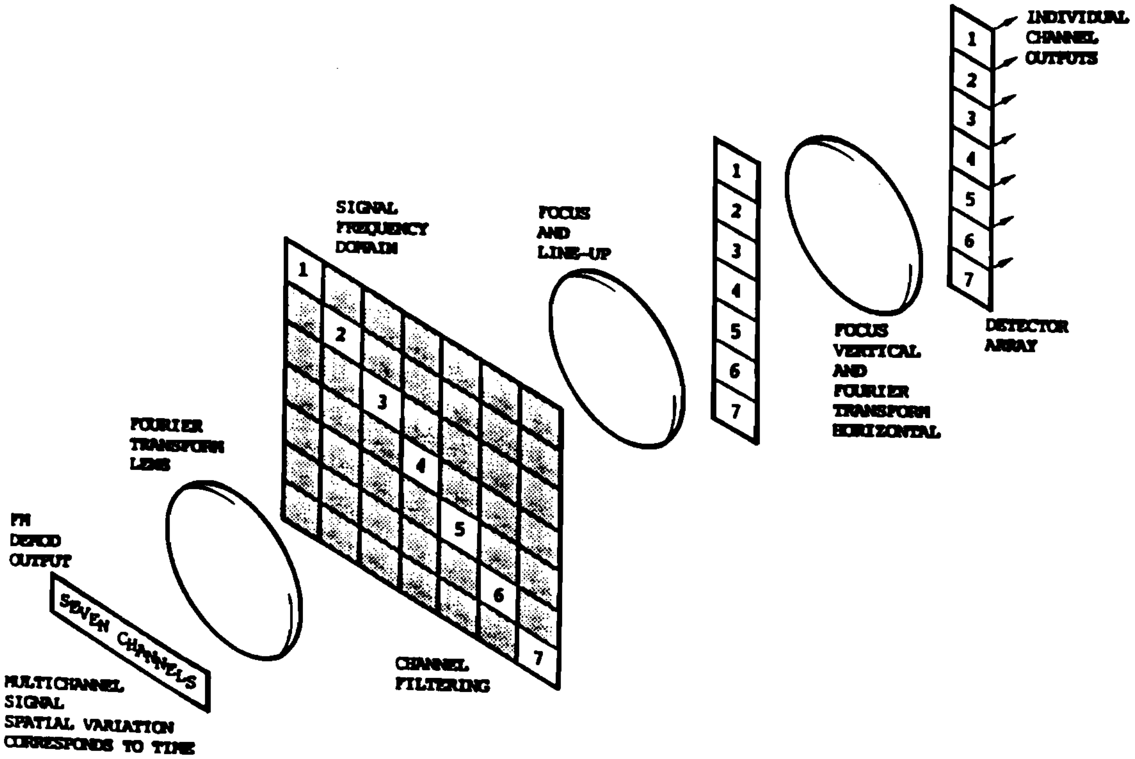


Figure 12. Optical demultiplexer for frequency-division-multiplex signal

nonlinearity. The operation performed by this device squares the envelope function of the main input beam and maintains at the output the same optical wavelength as the input. This will produce as a spatial waveform the amplitude modulation from the spatial microwave carrier input.

The separation of the frequency-division-multiplex of channels is alluded to in Figure 11, and then shown in detail in Figure 12. Staggered windows in the Fourier plane are used as channel dropping filters to provide each channel as a separate output impinging on its own photodetector element.

The analysis of the signal flow through the system is straightforward. The frequency modulated carrier at the input can be represented by the complex envelope:

$$[1 + m_v v(t - \frac{x}{s})] = \{1 + m_v A_i \cos [2\pi f_i(t - \frac{x}{s}) + \o_i(t - \frac{x}{s})]\} \quad (5)$$

where f_i, A_i, $\o_i$, and B_i are the frequency, amplitude, phase, and bandwidth of the microwave carrier. The output of the slope detection function is obtained by Fourier analysis.

$$a(t - \frac{x}{s}) = 1 + \frac{m_v A_i}{2} [1 + \frac{\frac{d}{dx}[\o_i(t - \frac{x}{s})]}{\pi B_i}] \cos [2\pi f_i(t - \frac{x}{s}) + \o_i(t - \frac{x}{s})] \quad (6)$$

Noncoherent amplitude detection by a squaring operation produces:

$$o(t - \frac{x}{s}) \approx 1 + \frac{m_v{}^2 A_i{}^2}{8} - \frac{m_v{}^2 A_i{}^2}{2} \frac{1}{B_i} (\frac{1}{2\pi s}) \frac{d}{dt} [\o_i(t - \frac{x}{s})] \qquad (7)$$

This accomplishes the frequency demodulation.

5. THE PHASE LOCKED LOOP

The Phase Locked Loop (PLL) plays a very significant role in analog signal processing, particularly for communications and radar signals. In fact, realization of an all optical PLL can provide confidence that most processing operations of interest can be accomplished, within the overall assumptions and constraints considered. The architecture of the PLL considered is identical to that of an electronic implementation, primarily because the major elements—the phase detector, the voltage controlled oscillator, and the loop filter—can be separately realized and analyzed. Other architectures, which more directly use four wave mixing and/or phase conjugation, are intriguing and worthy of further investigation.

A model of the optical phase locked loop is depicted in Figure 13. The output of the voltage controlled oscillator (VCO) provides the coherent reference for demodulation of AM or PM, typical applications of the PLL. In that case the loop filter function is chosen to synthesize a narrowband tracking loop to "phase lock" to the RF carrier component. Another application of the PLL is to synthesize an alternative FM demodulator, in which case the loop filter is designed for wideband (relative) signal tracking, realizing a narrower effective predetection bandwidth for a lower threshold demodulation than the discriminator.

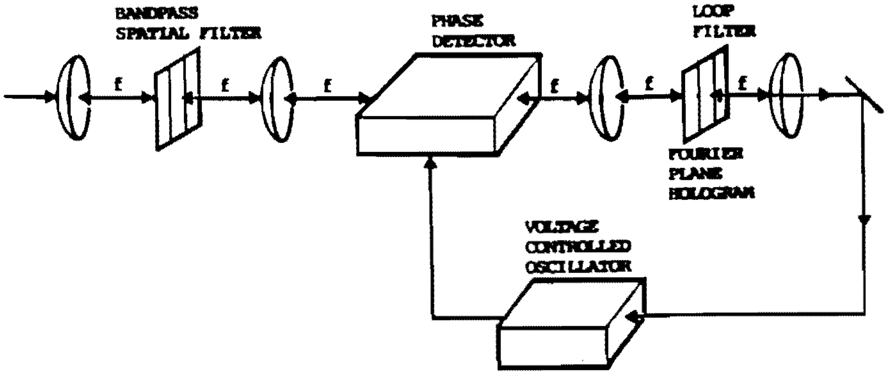


Figure 13. Model of all optical phase locked loop

The full optical implementation of the PLL is shown in Figure 14. Here the input is microwave; thus, the loop includes an acousto-optic spatial light modulator. In other typical applications the input is already optical and the PLL operates on the modulation of the optical beam. The closed loop accomplishes a locking of the voltage controlled oscillator to the input microwave phase variations. The purpose of the electronic local oscillator is to provide an unmodulated carrier waveform on the optical beam with the proper acoustic transverse propagation. The signal waveforms in the optical format all are double sideband spatial amplitude modulations. To accomplish this the VCO has the dual sideband structure of photorefractive devices, which frequency modulates the appropriate interference pattern. The phase detector utilizes a crystal, with a favorable third order nonlinearity, in the four wave mixing configuration, as a product device. It is basically a phase conjugate mirror with the signals to be multiplied modulated on the two pump beams. The loop filter is realized as a hologram to provide the required amplitude and phase characteristic. It can be synthesized from a spatial modulation form of the desired impulse response using well-known techniques. The other filters are simply aperture slots with a pair of Fourier transforming lenses.

This phase locked loop synthesis is a major building block in the thrust of optoelectronics for major signal processing operations. It utilizes optical components for which major developments are progressing, for other applications, such as phase conjugation and holography. It represents a significant blending of optical processing and communication system theory.

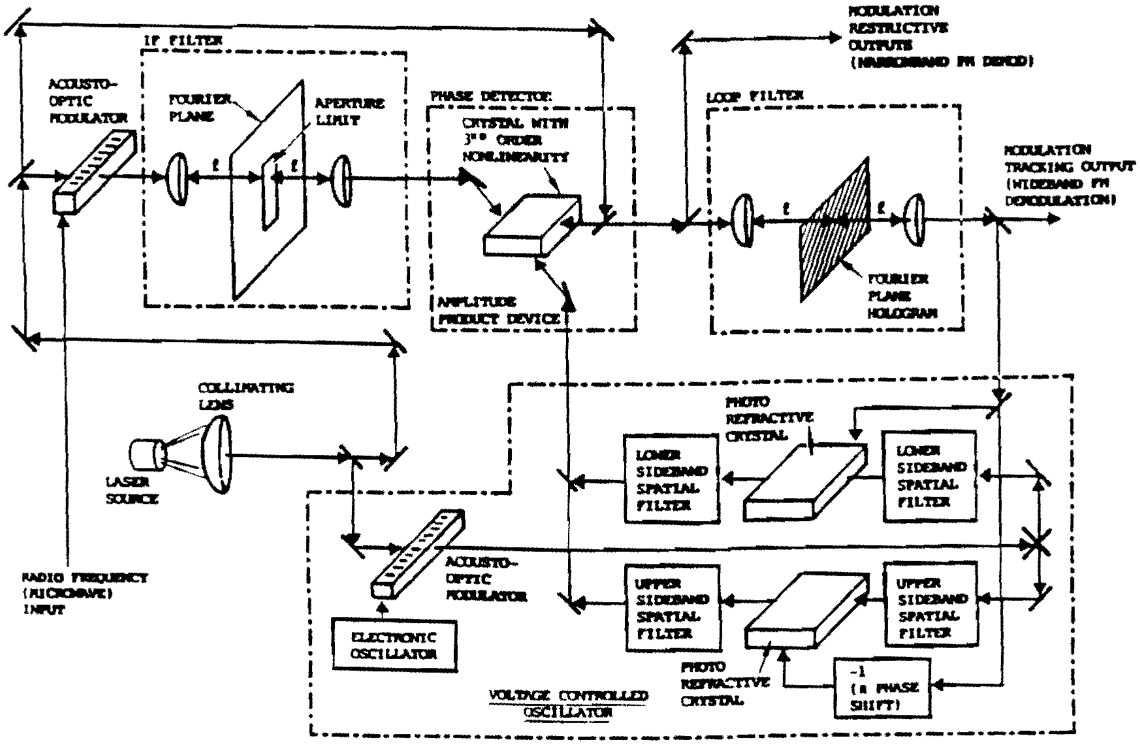


Figure 14. Optical implementation of electronic phase locked loop

6.SUMMARY

Presented herein are some example architectures for realizing electronic systems that employ optical processing techniques and components. After conversion of microwave (or RF) time varying signals to spatially varying properties of optical waves, all system operations are performed in the optical domain without transitioning back to electronics. This is a bridging between communication theory and modern optics, employing linear and nonlinear optics to directly realize the desired electronic system operations.

Optical processing of the form described herein, analog techniques, can provide certain advantages to communication systems. Fourier transforms can be performed readily. A second spatial dimension is available for parallel processing, such as exhaustive search of a signal space for signals and parameters of interest. The optical processors inherently provide wide bandwidth, high carrier frequency capability, and fast response. The spatial frequency domain makes it possible to operate separately on the positive and negative frequency regimes, an intriguing possibility. In many cases the channelized nature of communication systems matches very well the two dimensional structure of optical systems. Hopefully, electronic systems of the future will be able to capitalize on the rapid technological growth in optical devices and applications to provide ever increasing capability.

7. REFERENCES

1. D. P. Sullivan, "Analog Optical Processing of Radio Frequency Signals," published by Sierracom Inc., June 1990.

2. J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York, 1968.