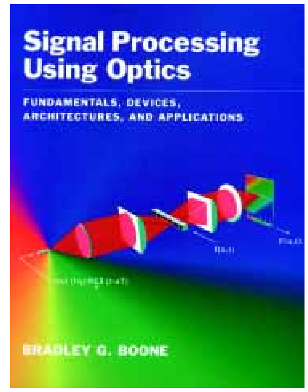
Optical Signal Processing

John N. Lee



SIGNAL PROCESSING USING OPTICS: FUNDAMENTALS, DEVICES, ARCHITECTURES, AND APPLICATIONS

Bradley G. Boone, The Johns Hopkins University Applied Physics Laboratory
Published by Oxford University Press, New York, 1998, 394 pp., $80.00

The student engineer who wishes ultimately to pursue R&D is well-advised to have a thorough grounding in fundamental topics, e.g., linear and nonlinear systems. Bradley Boone has published a textbook in optical signal processing that commendably leads the student from fundamental mathematical foundations to the fundamentals of physical optics, to relevant optical devices, all the way to specific examples of R&D applications. The treatment of the various topics also makes this book of value to students in optical technology and signal processing. Boone's book is not intended as a handbook on how to build optical processor hardware and systems, but rather describes the origins of a myriad of R&D approaches to harnessing the seeming advantages of optics for processing. These approaches have been varied and have been pursued by many brilliant researchers over the past decades. Although major applications have yet to emerge beyond a few niche areas, the intellectual diversity of optical processing, as exemplified by the range of R&D efforts described in this book, is a major reason I can unreservedly recommend this book, not only to the student, but to non-optical engineers who wish to see how much of R&D originated in this area. In my view, because optical processing is still in the research stage, it is a good illustration of the interdisciplinary nature of R&D in optical technology.

The book chapters flow in a logical sequence through the four topics of the book's subtitle. The book first covers the mathematical foundations of Fourier, Fresnel, Hilbert, and other well-known scientists. It then moves to physical principles developed by optical physicists, to descriptions of various optical device technologies such as light modulators and photodetectors, to descriptions of architectures that employ such devices to perform specific signal processing algorithms, and finally to specific real-world applications of general scientific interest. The four main topics, while clearly appropriate, also need to be shown as interrelated. Important interrelationships can be missing from texts that cover the individual topics in greater depth. But if the reader considers Boone's choice of application topics, one notices a selectivity determined by the constraints of the fundamental mathematical and physical device principles. Mathematical foundations and physical principles determine what kinds of signal processing operations are feasible. The repertoire of possible operations determines the types of devices that need to be developed, e.g., spatial light modulators. Physical principles determine device designs and limits to performance. Architectures for signal processing subsystems are dependent on the achievable device parameters. Different algorithmic approaches may need to be considered to circumvent device limitations. Finally, signal processing subsystems must be integrated into an application world that requires balanced operation among many functions, only one of which is the functioning of the optics. In the introduction, Boone gives his perspective on such interrelationships within the context of the history of and trends in optical processing; his emphasis is clearly, and correctly, on the importance of the fundamentals. I recommend looking at Figure 0.2 as a summation of this view—a series of ellipses pointing toward real-world applications but with mathematical foundations and physical principles central, followed by device technology and architecture and algorithms.

Chapter 1 discusses linear systems, but Boone highlights subjects that will be used to describe particular optical processing approaches. Hence, he emphasizes correlation, convolution, and Fourier transforms, as these were the basic operations shown early-on to be possible with optics. Linear transforms using matrix algebraic methods are also covered, with an eye toward image processing applications. The problem exercises and bibliography are very important parts of this chapter since the treatment here is selective.

Chapter 2 explains stochastic processes and nonlinear systems. The concepts of stochastic processes and probability density functions are used to complete the description of the correlation process and its relation to matched filtering. The examples emphasize time-series signals rather than imagery, probably in anticipation of optical processors that operate on time-series data. Nonlinear systems are discussed with regard to optical processing light modulators and photodetectors.

Many modulators have limited dynamic range and therefore use only two levels to describe information (binarization); the impact of such necessities on processing performance is covered very succinctly and nicely. Also, nonlinear transfer functions are desirable in many optical devices, such as for image processing and digital optical computing; the effects of hardclipping and sigmoid functions on Fourier transformation and correlation are discussed. Mixing and modulation are then discussed, including the nonlinear mixing products that occur in real devices and limit the dynamic range of analog optical processors handling multiple signals.

Chapter 3 describes several mathematical transforms used in optical signal processing (in addition to the Fourier transform): Fresnel, Hilbert, Radon, Mellin, and wavelet transforms. All can be performed optically, and some are important for describing how optical processors work, e.g., how they handle complex signals (Hilbert transform), or how light propagates in optical processors (Fresnel transform). As with Chapter 1, the problem exercises and bibliography are particularly important parts of this chapter.

Chapters 4 and 5 discuss fundamentals of optics: properties of light, geometrical optics, and physical optics, including coherency, as well as Fresnel and Fraunhofer diffraction. Special topics concerning optical processor requirements include anamorphic optics using prisms and replication of an image into an array of identical images using multifaceted prisms and lenslet arrays. A more comprehensive discussion of holography would have been desirable since holographic matched filters and spatial light modulators are discussed in later chapters.

Chapter 6 describes the basis of the earliest optical processor, namely, the Fourier transform properties of a simple lens. The so-called 4-f lens configuration for Fourier transformation is explained toward the end of the chapter. The discussion of the optical transfer function, point spread function, and signal processing analogies for optics should be particularly helpful to the electrical engineer with no background in optics.

Chapter 7 discusses the critical area of light sources and detectors. Although basic principles of operation for LEDs, lasers, and photodetectors are covered, the more demanding performance parameters pertaining to optical processors are emphasized. Only semiconductor laser diodes are considered; although not stated explicitly, laser diodes are almost invariably the only option in practical optical processors. Also, the trade-off between duty cycle and coherence for laser diodes is discussed; this is an important consideration where optical modulation is done by directly modulating the current to the laser diode.

Similarly, various types of photodetector arrays are described. An important section on optical signal processing requirements is provided, elucidating the differences from conventional uses such as for communications and sensing.

Chapter 8 on spatial light modulators is again device oriented. Although spatial light modulators are often modified from other uses, particularly light-beam deflection and image display devices, the performance parameters are much more severe than in the broader uses. Acousto-optic devices are given special consideration, even though they are only one-dimensional devices, because they offer very high efficiency with reasonable speed and resolution. A number of two-dimensional spatial light modulators are described in terms of various physical phenomena: liquid crystals, magneto-optics, electro-optics, electroabsorption, deformable membranes, and electron beam physics. Boone advances an interesting conjecture about two-dimensional spatial light modulators concerning the difficulty to date in obtaining devices that have both high frame rate and high spatial resolution: the product of electro-optic efficiency and speed of response is basically a constant for a given spectral bandwidth, analogous to the trade-off arising from a constant gain-bandwidth product in electrical amplifiers.

Chapter 9 describes the broad development of spectral analysis and correlation techniques with optics. This chapter deals only with time-series signal analysis and mainly acousto-optic architectures. Time-integrating versus space-integrating architectures, and incoherent architectures versus coherent ones (using the phase of the light to convey information), are included. Boone discusses how an accurate Fourier transform can be obtained with devices of limited precision such as liquid crystal televisions. He also describes the quantitative decrease in mean square error with increasing signal precision (described by number of bits in a digital representation of the signal).

Chapter 10 considers spatial filtering and correlation for two-dimensional images. The chapter describes the VanderLugt method for generating a matched filtering function in the Fourier transform plane, spatial filtering in the Fourier plane, correlation performance with binary- and phase-only matched filters, spatial multiplexing to exploit the full parallelism of two-dimensional optics, distortion-tolerant correlation, and correlation in angular, rather than Cartesian, coordinates.

Chapter 11 describes two important applications of optical processing for radar: ambiguity function processing for range-Doppler, and synthetic aperture radar image formation. The necessary radar concepts are first described clearly and succinctly. The emphasis is on acousto-optic implementations for these two applications. This chapter shows how developments in algorithms and devices are interrelated. Acousto-optic devices are the most effective spatial light modulators, but they are only one-dimensional; the two applications considered here are two-dimensional, however. A powerful algorithmic approach was developed to handle the two-dimensional problems: factoring into one-dimensional terms that can be implemented with a series of acousto-optic devices, and orthogonally for two-dimensional processing. The resultant triple- and four-product acousto-optic processor has been applied to a wide range of problems and may soon become available as a commercial product. Additional topics are introduced in the problem sets, such as direction-of-arrival processing and generation of Wigner functions with the architectures described in this chapter.

Chapter 12 covers a range of research topics in pattern recognition and image processing. The triple-product processor working in conjunction with two-dimensional spatial light modulators is presented as a versatile architecture for several algorithms. This approach leads to a discussion of matrix-vector, or more generally, linear algebraic optical processors. It is important for the reader to recognize that such matrix processors are not meant to perform numerical computations, but rather provide a paradigm for development of optical processing approaches to various signal and image processing tasks. Hence, there follows a discussion of the discrete Fourier transform as a matrix-vector operation, and the casting of simple neural network problems, such as those employing the Hopfield net, as matrix-vector multipliers incorporating thresholding, feedback, and gain.

I believe that this book will be a valuable one for the senior-level undergraduate and the first-year graduate student, as Boone intended. The practicing engineers and scientists that would profit are those who do not have sufficient background in optical technology. It is my hope that many of these engineers and scientists will be those that can fit the optical processing concepts described here into system-level electronic hardware and control software.

Dr. John N. Lee
Head, Optical Information Processing Section
Advanced Concepts Branch
Optical Sciences Division
Naval Research Laboratory
Washington, DC 20375
lee8@ccsalpha2.nrl.navy.mil