Optical Fourier transform techniques for advanced Fourier spectroscopy systems

David Casasent and Demetri Psaltis

A review of multichannel long integration time, optical Fourier transform techniques for advanced Fourier spectroscopy systems is followed by the description of a new multichannel time-integrating optical Fourier transform chirp-Z system and a discussion of its use in Fourier spectroscopy signal processing.

I. Introduction

The superiority of Fourier spectroscopy techniques over grating spectrometers is well known.[1–3] The general Fourier spectroscopy (FS) interferogram $f(x)$ can be described by the cosine Fourier transform (FT) of the desired spectral distribution $F(\nu)$[4]:

$$f(x) = \int_{\nu_1}^{\nu_2} F(\nu) \cos 2\pi\nu x d\nu, \tag{1}$$

where ν_1 and ν_2 are the minimum and maximum wave numbers in the spectral distribution. The purpose of a FS signal processor is to compute $F(\nu)$ from $f(x)$. In recent years[5,6] considerable attention has been given to various real-time digital FT techniques to calculate the spectral distribution from the corresponding interferogram.

As typical examples, we consider two specific presently available FS systems[7]: (1) a single detector system with 10-sec integration time and 2400-Hz bandwidth; and (2) a system with sixteen detectors, 0.1-sec integration time, and 250-Hz bandwidth. Recent advances in smart sensors are rapidly increasing our ability to obtain quite extensive interferogram information.[5,6] These advanced systems will use imaging spectrometers with 1000 separate imaging detector areas, integration times in excess of 10 sec, and large bandwidths above 2 kHz. For this reason, advanced multichannel FT techniques such as optical signal processing merit attention.

The parallelism of an optical processor appears to be of most use in such multisensor advanced FS systems. For this reason, we consider only those optical FT techniques with multichannel capacity. In Secs. II–IV we review various parallel and real-time optical FT techniques with attention to their appropriateness for this advanced FS signal processing problem. This review of optical FT techniques also serves as an excellent summary of the advantages, disadvantages, and state of the art of optical signal processing. A new multichannel chirp-Z optical FT system capable of the required performance is then described in Sec. V.

II. Classical Optical FT Systems

The FT relationship that exists between the light distribution in the front and back focal planes of a lens illuminated with coherent light has been the hallmark of optical computing. A multichannel 1-D optical FT system results if a cylindrical/spherical lens set is used. These 2-D optical signal processors require the use of real-time and reusable 2-D spatial light modulators (SLMs) on which to record the input data. Although considerable progress has been made on these components in recent years,[8] they remain the major shortcoming of such 2-D parallel optical FT systems. For this multichannel FT application, the addressing scheme (by which above 1000 parallel signals are recorded on 1000 separate lines on a SLM) is the second major problem area. For these reasons, most of the recent work on optical signal processing has focused on systems employing acoustooptic (AO) transducers,[9] because of their availability and reliability. Thus, the majority of this review will address such practical optical signal processing systems.

The major disadvantage of AO transducers is that they are 1-D devices, whereas an optical processor is a 2-D system, and the FS application of concern requires 2-D signal processing. It can be shown that multi-

The authors are with Carnegie-Mellon University, Department of Electrical Engineering, Pittsburgh, Pennsylvania 15213.

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channel AO transducers cannot be fabricated with channel separations below 3 mm due to dispersion effects.[10] Thus, alternate system architectures are necessary to realize parallel processing with conventional AO transducers.

The long duration (>10 sec) and modest bandwidth (>2 kHz) signals of concern in FS represent an input time–bandwidth product in excess of 20,000. This is beyond the state of the art of the 1-D space–bandwidth product of present optical transducers.[11] The folded spectrum optical processor[12] in which the 2-D FT of a raster recorded 1-D signal is formed can solve this problem. The resultant FT pattern is a folded spectrum with coarse and fine frequency axes. However, such a system is not directly adaptable for our multichannel long duration and high space–bandwidth product FT application without extensive research on the input addressing system, the lens system, and the 2-D SLM required.

III. AO Signal Processors

For the reasons noted in Sec. II, new AO signal processing architectures will receive major attention in this review. The classic AO FT system is a space-integrating one[13] in which the optical FT of the signal in the AO cell is formed in space in the output FT plane. In this system, input signal $f(t)$ (whose FT is desired) is fed to an AO cell that is illuminated with parallel light. The transmittance of the AO cell varies in time t and space x as $f(t - \tau)$, where $\tau = x/v$, and v is the acoustic velocity of the wave in the medium. The optical FT of this pattern is thus a function of time and the input spatial frequency

$$F(\omega_x,t) = \int_t^{t+T} f(t - \tau) \exp(-j\omega_x\tau)d\tau. \qquad (2)$$

The disadvantages of this space-integrating AO system for the FS application are (1) its 1-D nature (it is not directly extendable to multichannel applications), (2) the short aperture time of the cell (this limits the integration time to approximately 100 μsec maximum), and (3) the large bandwidth of the cell (50 MHz–1 GHz which cannot be fully exploited in this application). Such a system is more appropriate for wideband and radar signal processing applications.

Application of the chirp-Z algorithm[14] allows FTs to be performed using convolvers,[9,15] which are the basic building blocks of optical signal processors. To describe how such systems can be realized, we rewrite the 1-D FT as

$$F(\omega) = \int f(x) \exp(-j\omega x)dx, \qquad (3)$$

using

$$(\omega - x)^2 = (x - \omega)^2 = \omega^2 + x^2 - 2\omega x, \qquad (4)$$

as

$$F(\omega) = \exp(-j\omega^2/2)[f(x) \exp(-jx^2/2) \circledast \exp(+jx^2/2)] \qquad (5a)$$

$$= \exp(-j\omega^2/2)[f(t) \exp(-jt^2/2) \circledast \exp(+jt^2/2)]. \qquad (5b)$$

In the form in Eq. (5a), an integration in space is implied, and the frequency output variable is usually time,

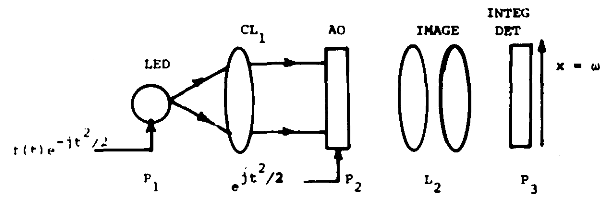

Fig. 1. Schematic diagram of a time-integrating chirp-Z acoustooptic Fourier transform system.

whereas in Eq. (5b), an integration in time is implied, and the frequency output variable is usually space.

These two realizations are referred to as space-integrating (SI) and time-integrating (TI) chirp-Z convolvers, respectively, after the basic SI and TI AO processors.[16,17] In such an AO system, the FT is realized by multiplication of the input signal by a chirp [$\exp(-jx^2/2)$ or $\exp(-jt^2/2)$] and convolution of this signal with another chirp [$\exp(+jx^2/2)$ or $\exp(+jt^2/2)$]. If the magnitude of the FT is not sufficient, the exact FT can be obtained by multiplication of the output pattern by another chirp [$\exp(-j\omega^2/2)$]. Coherent or noncoherent light can be used. The SI chirp-Z FT system requires only a single output plane detector since the output FT appears as a function of time. Its disadvantages are that it is not directly extendable to multichannel processing and more so that the integration time possible is still too low (the aperture time of the AO cell).

Conversely, the TI chirp-Z FT system (Fig. 1) has a large (essentially ∞) integration time and hence a very large input time–bandwidth product, whereas the output space–bandwidth product limits the frequency resolution obtainable. This system has the large integration time necessary for the FS application and moderate bandwidths. The system directly realizes Eq. (5b). The input signal is modulated by a chirp and used to time sequentially modulate the linear intensity from a LED, laser diode (LD), or other light source. This output is collimated to illuminate uniformly the AO cell that is fed by another chirp. The AO cell is imaged onto the output detector where the resultant signal is integrated in time, and the FT in Eq. (5b) is displayed in space. This system is most attractive for our FS application since use of a chirp with duration T much greater than aperture time τ of the AO cell enables long integration times and moderate bandwidths desired in the FS application to be obtained. In Sec. V we discuss a multichannel version of this system.

We note that the basic TI system performs a convolution, whereas using chirp-Z techniques, it can also realize the FT operation. Extensions of the basic TI AO system to multidimensions (using two crossed AO cells) allow folded spectrum and ambiguity function 2-D outputs to be obtained from 1-D input data using only 1-D transducers.[9,18–21] Hybrid time and space-integrating AO folded spectrum FT processors have been recently described.[22,23] These systems exhibit the advantages of both the TI and SI systems.

IV. Vector–Matrix Noncoherent FT Systems

The accuracy of an optical computer is a continuously voiced concern. Optical residue arithmetic systems[24,25] and optical numerical processors[26] have been developed to address this issue. These latter systems can best be described as vector–matrix multipliers. In one version of such a system,[26] the input source is a linear array of LEDs (the outputs from these LEDs describe components f_m of input vector **F**). This vertical LED array is imaged vertically and expanded horizontally onto a 2-D mask with transmittance $m_{n,m}$ (the elements of the matrix M). The output light from the mask is imaged horizontally and integrated vertically onto a linear horizontal output detector array. The output is then the vector–matrix product $\mathbf{G} = M\mathbf{F}$ or

$$g_n = \sum_m m_{n,m} f_m. \tag{6}$$

This system can be used to perform the DFT by considering the M samples of input signal f to be M components of input vector **F**. The elements of the matrix mask are then chosen to be the corresponding Fourier kernel samples

$$m_{n,m} = \exp(-j\pi 2\pi nm/N). \tag{7}$$

The N components of output vector **G** are now the corresponding Fourier coefficients in the FT of f. Complex functions can be handled by various other techniques in the system.[26] The final optical FT system to be considered combines advances in solid-state source and detector technology to produce accurate optical FTs. A multichannel system of this type would require multiple linear laser diode and photodiode arrays. Moreover, for the present FS problem, the number of linear source and detector elements necessary is too excessive for present technology (in excess of 20,000 laser diode and photodiode elements are required in each linear array).

V. Multichannel Optical FS Signal Processor

In Fig. 2 we show a multichannel version of the TI chirp-Z AO FT system of Fig. 1. A multichannel system has been obtained by use of a linear array of laser diode or LED input sources. Each laser diode source is fed with one of the N spectrometer signals $f_1 - f_N$, after premultiplication via chirp. The AO cell is modulated by a similar chirp. For each channel, the light distribution leaving the AO cell is $f_n(t)\exp(-jt^2/2)\exp[j(t - \tau)^2/2]$. This pattern is imaged onto the linear output detector array where an integration in time occurs. (Single sideband modulation and other practical features of this system are ignored for simplicity in this discussion.) The integrated detector output in one channel is

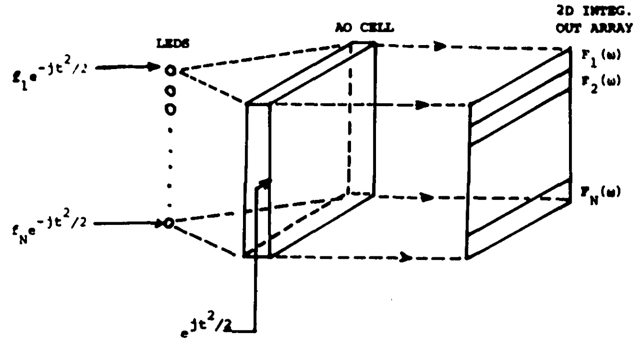

Fig. 2. Schematic diagram of a multichannel electrooptical Fourier transform system for advanced Fourier spectroscopy signal processing.

$$F_n(\omega) = F_n(x) = \int f_n(t)\exp(-jt^2/2)\exp[j(t - \tau)^2/2]dt$$
$$= [f_n(t)\exp(-jt^2/2) \circledast \exp(jt^2/2)], \tag{8}$$

or the desired FT in Eq. (5b).

This system exhibits the long integration time advantage of the TI convolver and a small and compact solid state input source array for multichannel performance. The output from each LED can be expanded by fiber optics to illuminate uniformly the AO cell, and, with single sideband modulation performed on the AO cell output with optical filters, a compact system is possible.

To quantify the use of this system in advanced FS signal processing, we consider a FS system with 100 detector areas, 2.5-sec sweep time for the spectrometer, and 2-kHz signal bandwidth. As our system input, we use a linear array of 100 laser diodes. (Such arrays can be fabricated in less than 10 mm.[27] The linearity of the input voltage without light intensity for laser diodes is superb with over a 60-dB linear dynamic range possible.) For the AO cell we assume 100-MHz bandwidth with 50-μsec aperture time. (Such devices are likewise available commercially.[9]) Since the bandwidth of the AO cell exceeds the bandwidth of the input signal by a factor of 5×10^4, we can attain an integration time that is 5×10^4 times the aperture time or 2.5 sec as desired. The corresponding frequency resolution of this system is 0.4 Hz.

Thus, the parallel electrooptical FT system as shown (with only moderate component specifications) is capable of performing over 100 parallel multichannel FTs on FS signals of 2.5-sec duration with 0.4-Hz resolution over a 2-kHz signal bandwidth. Many alternate versions of this system architecture are possible using other devices such as surface acoustic wave transducers.[28] Other versions of this system such as the triple product processor[20] perform a more powerful signal processing operation such as correlation and ambiguity function generation.[21] Such advanced electrooptical signal processing techniques appear most attractive for advanced sensor systems.

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References

1. J. Connes and P. Connes, J. Opt. Soc. Am. **56,** 896 (1966).
2. G. Vanasse *et al.*, Eds., *Aspen 1970 International Conference on Fourier Spectroscopy,* AFCRL 710019 (5 Jan. 1971).
3. G. Vanasse and H. Sakui, Prog. Opt. **6,** 260 (1967).
4. J. E. Hoffman, Jr. and G. A. Vanasse, Appl. Opt. **5,** 1167 (1966).
5. G. A. Vanasse, Ed., "Multiplex and/or High-Throughput Fourier Spectroscopy," Proc. Soc. Photo-Opt. Instrum. Eng., Vol. **191,** (Aug. 1979).
6. G. Vanasse, R. Esplin, and R. Huppi, Opt. Eng. **18,** 403 (1979).
7. G. Vanasse, Air Force Geophysics Laboratory; private communication.
8. Special issue on "Spatial Light Modulators," Opt. Eng. **17** (July 1978).
9. T. F. Tao, Ed., "Real-Time Signal Processing," Proc. Soc. Photo-Opt. Instrum. Eng., Vol. **180** (Apr. 1979).
10. D. L. Hecht, Itek Applied Technology, Inc.; private communication.
11. D. Casasent, Proc. IEEE **65,** 143 (1977).
12. C. E. Thomas, Appl. Opt. **5,** 1782 (1966).
13. D. L. Hecht, Proc. Soc. Photo-Opt. Instrum. Eng. **90,** 148 (1976).
14. L. Rabiner *et al.*, IEEE Trans. Audio **AU-17,** 86 (1969).
15. H. Whitehouse, R. Means, and J. Speiser, IEEE Trans. Circuits Syst. (Apr. 1975).
16. L. J. Cutrona, E. N. Leith, C. J. Palermo, and L. J. Procello, IRE Trans. Inf. Theory **IT-6,** 386 (1960).
17. R. A. Sprague and C. L. Kolipoulos, Appl. Opt. **15,** 89 (1976).
18. T. M. Turpin, Proc. Soc. Photo-Opt. Instrum. Eng. **154,** 196 (1978).
19. P. Kellmen, Proc. Soc. Photo-Opt. Instrum. Eng. **154,** 196 (1978).
20. J. Spieser and H. Whitehouse, NOSC, NUCTN 1355R, San Diego (1974).
21. J. D. Cohen, Proc. Soc. Photo-Opt. Instrum. Eng. **180,** 134 (1979).
22. T. R. Bader, Appl. Opt. **18,** 1668 (1979).
23. D. Psaltis and D. Casasent, Appl. Opt. **18,** 3203 (1979).
24. A. Huang, Y. Tsunoda, J. W. Goodman, and S. Ishihara, Appl. Opt. **18,** 149 (1979).
25. D. Psaltis and D. Casasent, Appl. Opt. **18,** 163 (1979).
26. J. W. Goodman *et al.*, Opt. Lett. **2,** 1 (1978).
27. W. T. Tsang, R. A. Logan, and R. P. Salathe, Appl. Phys. Lett. **34,** 162 (1979).
28. N. Berg *et al.*, Opt. Eng. **18,** 420 (1979).

Books *continued from page 2024*

Handbook of Optical Holography. Edited by H. J. CAULFIELD. Academic Press, New York, 1979. 638 pp. $39.75.

This is a good book. It has just the right mix of fundamental, rigorous theory and practical applications to hold the interest of anyone working, not only in holography, but in any field of optics, nay, in any of the physical sciences at all. Despite my personal dislike of mere anthologies of (incoherent) chapters by unrelated authors, this book is different. The contributors, thirty-one all told, are the top names in holography. Their writings seem well edited; they are concise, to the point, and of about compatible sophistication (as far as this is possible with topics ranging far and wide); in short, it all fits together very well.

The material is divided into ten large groups and these into fifty-three chapters. In this review I will merely list the chapter headings and mention in more detail only the really outstanding contributions, both theoretical and applied.

It all starts out with a most excellent Introduction (Chap. 1) by **E. N. Leith.** Group 2 contains, no pun intended, the Background, with contributions on Integral Transforms (**K. Dutta**), Interference and Diffraction and Partially Coherent Light (both by **B. J. Thompson**), Image Evaluation (**F. T. S. Yu and A. Tai**), Communication Theory (**J. B. DeVelis** and **G. O. Reynolds**), and a particularly good, detailed, and well-written chapter on Silver Halide Photography (**P. L. Bachman**). Group 3 deals with the Classification of Holograms (**W. T. Cathey**). In Group 4 we find Major Hologram Types, listing, for example, the various cases of on-axis and off-axis Fresnel Holography (**J. B. DeVelis** and **G. O. Reynolds**); Fraunhofer Holograms (**B. J. Thompson**); and Fourier Holography (**H. H. Arsenault** and **G. April**).

Then follows Group 5 with Variations to the theme: Multiplexed Holograms, Color Holograms, Polarization Holograms, and Local Reference Beam Holograms (all by **W. T. Cathey**) and Reflection Holograms and a particularly clear exposition of Synthetic Holograms (both by **H. J. Caulfield**). Group 6 is all Image Formation (**J. Upatnieks**), and Group 7, Cardinal Points and Principal Rays for Holography, expounds the analogy between lenses, zone plates, and holograms (**H. H. Arsenault**).

Group 8 turns to Equipment and Procedures, with chapters on Solid State Lasers (**W. Koechner**), Gas Lasers (**N. Balasubramanian**), a very useful description and tabulation of Recording Media (**J. W. Gladden and R. D. Leighty**), and Holographic Systems, with numerous diagrams of experimental setups (**R. L. Kurtz, H.-K. Liu,** and **R. B. Owen**).

Now we come to the nuts and bolts of holography and how to do it. Group 9, Special Problems, again is concerned with Photographic Materials and Their Handling, with emphasis on Agfa-Gevaert 8E75, Eastman Kodak 120, and other emulsions, and the author's own PAAP developer (**S. A. Benton**); Speckle, which, while useful in other areas, is often a problem in holography (**H. J. Caulfield**); and Hologram Copying, which, because of the high space frequencies, is much more difficult than copying in conventional photography (**W. T. Rhodes**).

Group 10, Application Areas, is perhaps the most fascinating part to read. Holography, clearly, is not anymore a "discovery looking for a job." There is now a plethora of applications, from the mundane (viewing a hologram at the local science fair) to the exotic (synthetic movies). The list of chapters in this group reads Digital Data Storage, with many good diagrams and cost, efficiency, access time, noise, and other considerations (**T. K. Gaylord**); 2-D Displays (**B. R. Clay**); and 3-D Displays, the subject that, of course, really fired the imagination of laymen and researchers alike and that here is presented in a very lucid, easy-to-read way (**M. Lehmann**). This chapter includes rainbow and multiplex holography, holographic movies, projection and other display systems, decorative holography, and holographic methods for the display of art objects (and of pathologic specimens, replacing bulky, foul-smelling glass containers). The applications part moves on to Holographic Interferometry (**B. G. Brandt**) who emphasizes correctly the similarity between holographic recording and, say, the Mach-Zehnder interferometer and discusses vibration analysis, stroboscopic techniques, data reduction, and real-time interferometry; Pattern and Character Recognition, a very detailed and rigorous contribution (**D. Casasent**); Image Processing including image deblurring, contrast enhancement, and theta modulation (**S. H. Lee**); Microscopy (**M. E. Cox**); Optically Recorded Holographic Optical Elements, from simple lenses to systems that can perform

continued on page 2040