NAIC-ID(RS)T-0388-94

NATIONAL AIR INTELLIGENCE CENTER

AIR INTELLIGENCE AGENCY

APPLIED RESEARCH ON LIQUID CRYSTAL SPATIAL MODULATORS IN HADAMARD TRANSFORM SPECTROMETERS--QUICK AND ACCURATE DECODING METHODS

by

Zhang Bingquan, Bi Fengfei

NATIONAL AIR INTELLIGENCE CENTER

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

APPLIED RESEARCH ON LIQUID CRYSTAL SPATIAL MODULATORS IN HADAMARD TRANSFORM SPECTROMETERS--QUICK AND ACCURATE DECODING METHODS

Zhang Bingquan Bi Fengfei

ABSTRACT

This article studies liquid crystal spatial light modulator (LC-SLM) functioning as a fixed, unmoving encoding mask applied in Hadamard transform spectrometers (HTS). It puts forward a fast and accurate decoding method, and offers improvements in root mean square signal to noise ratios associated with liquid crystal spatial light modulators.

Key Terms liquid crystal spatial light modulator, encoding mask, Hadamard transform spectrometer, decoding method

1. INTRODUCTION

Hadamard transform spectrometers (HTS) were developed at the end of the 1960's and are a type of Fourier transform spectrometer parallel multichannel transmission modulation spectrometer. Harwit, Decker, Sloane, et al, have done a great deal of work in this area [1-6]. They, among traditional spectrometers, use encoding masks to replace incident slits or output slits. Normally, use is made of mechanical masks to act as Hadamard transform spectrometer encoding masks. Due to not only slow scanning speeds associated with mechanical masks but also the existence of relatively large mechanical errors, applications of them are limited in the molecular spectral analysis realm. Because of this, in 1987, Tilotta, et al [7], made the first use of liquid crystal spatial light modulators

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

(LC-SLM) to act as encoding masks. In conjunction with this, designs were done for Hadamard transform spectrometers associated with fixed and unmoving encoding masks. These, for future spectral analysis, offered spectrometers without "moving parts". Use was made of them in measurements of visible spectra, near infrared spectra, as well as visible Raman spectra, achieving great successes [7,8]. In 1989, Bohlke, et al [9], also used them, after adding improvements, in measurements of near infrared Raman spectra, pioneering a new path for measurements of near infrared Raman spectra. This article sets out from error theory and puts forward a fast and accurate decoding method to be used when LC-SLM function as encoding masks. In conjunction with this, from this, are deduced relationships between switch characteristics associated with LC-SLM encoding masks and root mean square signal to noise ratio improvements.

2. FAST AND ACCURATE DECODING METHODS

Letting the encoding unit number be n, there are n individual spectral components awaiting measurement. Using n individual masks, n measurement iterations are carried out. The error of the ith measurement is e_i. Assume [6]: (1) e_i is not dependent on the random variable of probe light strength; (2) the expected value for e_i is zero; (3) errors for the various iterations of measurement are mutually independent; (4) the mean square deviation associated with e_i is σ^2. One then has

$$E\{e_i\}=0, \quad E\{e_i \cdot e_j\}=0, \quad E\{e_i^2\}=\sigma^2. \qquad i,\ j=1,\ 2,\ \cdots,\ n \quad i \neq j \tag{1}$$

In the equations, E represents the expected value or the average value in a large number of tests. Based on the assumptions made above about errors, it is possible to obtain errors e_1, e_2, ..., e_n, associated with n iterations of measurement. When n is very large, one has /603

$$\frac{1}{n}\sum_{i=1}^{n} e_i = 0. \qquad (2)$$

Reference [7] clearly shows that LC-SLM opening and closing characteristics created by the improved fitting of AND Company Model 12A torque direction arranged liquid crystal display units are very stable in spectral responses associated with the visible light spectral area (350nm - 800nm). The average value for transmission rates when passing light is 32%. The average value for transmission rates when not transparent is 1.5%. Reference [9] clearly shows that when PDLC (polymer dye liquid crystals) are used as LC-SLM, opening and closing characteristics associated with the near infrared ($10000cm^{-1}$ - $5500cm^{-1}$) spectral area are also very stable. When passing light, transmission rates vary between 78%-81%. When not transparent, transmission rates vary between 2%-11%. On the basis of the facts described above, obviously, it is possible, in one section of spectral area, to take LC-SLM opening and closing characteristics as a constant. In different spectral areas, the constants are different.

Assume, when liquid crystal mask encoding units pass light, that transmission rates are T_h. When not passing, transmission rates are T_0. Mask encoding element opening and closing is carried out with each line matrix element associated with a left cyclic S matrix S_n with an M order structure. That is, when the corresponding matrix element is 1, the equivalent encoding element of the mask passes light. When the corresponding matrix element is 0, the relevant encoding element of the mask is not transparent. Taking matrix element 1 of S_n and changing it to be T_h and taking matrix element 0 and changing it to be T_0, it is possible to obtain the mask's actual encoding matrix S'_n. S'_n can be shown to be

$$S'_n = T_h S_n + T_0(J_n - S_n) = (T_h - T_0)S_n + T_0 J_n, \qquad (3)$$

In the equations, J_n is an nth order equation with all matrix elements as 1. The nature of S matrix as well as S matrix characteristics associated with M order structures can be seen in Reference [6]. Assume that the energy added to mask encoding elements is represented by the use of signal vector ψ. ψ is then the vector for the actual spectral component strength value awaiting measurement. Use η to represent measurement value vectors. One then has

$$\eta = S'_n\psi + e. \tag{4}$$

Still in accordance with decoding methods when S_n acts as the mask encoding matrix, carry out decoding. In conjunction with this, make use of equations (3) and (4) to obtain actual spectrum estimate values (initial) $\hat{\psi}$ which are

$$\hat{\psi} = S_n^{-1}\eta = (T_h - T_0)\psi + \frac{2T_0}{n+1}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{i=1}^{n}\psi_i + S_n^{-1}e, \tag{5}$$

Summing the individual components of the vectors on the two sides of the equal signs in equation (5), it is possible to obtain

$$\sum_{i=1}^{n}(\hat{\psi})_i = \sum_{i=1}^{n}[(T_h - T_0)\psi]_i + \sum_{i=1}^{n}\left\{\frac{2T_0}{n+1}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{j=1}^{n}\psi_j\right\}_i + \sum_{i=1}^{n}(S_n^{-1}e)_i. \tag{6}$$

Calculating the various terms in equation (6), one has

$$\left.\begin{aligned}
&\sum_{i=1}^{n}(\hat{\psi})_i = \sum_{i=1}^{n}\hat{\psi}_i,\\
&\sum_{i=1}^{n}[(T_h - T_0)\psi]_i = (T_h - T_0)\sum_{i=1}^{n}\psi_i,\\
&\sum_{i=1}^{n}\left\{\frac{2T_0}{n+1}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{j=1}^{n}\psi_j\right\}_i = \frac{2T_0 n}{n+1}\sum_{i=1}^{n}\psi_i,\\
&\sum_{i=1}^{n}(S_n^{-1}e)_i = \frac{2}{n+1}\sum_{i=1}^{n}[(2S_n - J_n)e]_i = \frac{2}{n+1}\left[\sum_{i=1}^{n}(2S_n e)_i - \sum_{i=1}^{n}(J_n e)_i\right]\\
&\qquad = \frac{2n}{n+1}\cdot\frac{1}{n}\sum_{i=1}^{n}e_i = 0.
\end{aligned}\right\} \tag{7}$$

Taking equation (7) and substituting in equation (6), one has

$$\sum_{i=1}^{n}\psi_i=\frac{n+1}{(n+1)T_h+(n-1)T_0}\sum_{i=1}^{n}\hat{\psi}_i, \qquad (8)$$

$$\hat{\psi}=(T_h-T_0)\psi+\frac{2T_0}{(n+1)T_h+(n-1)T_0}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{i=1}^{n}\hat{\psi}_i+S_n^{-1}e, \qquad (9)$$

Then,

$$\frac{1}{T_h-T_0}\left(\hat{\psi}-\frac{2T_0}{(n+1)T_h+(n-1)T_0}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{i=1}^{n}\hat{\psi}_i\right)=\psi+\frac{1}{T_h-T_0}S_n^{-1}e. \qquad (10)$$

Assuming spectrum estimate values have been corrected, use $\hat{\psi}_{MODI}$ to represent them. Make

$$\hat{\psi}_{MODI}=\frac{1}{T_h-T_0}\left(\hat{\psi}-\frac{2T_0}{(n+1)T_h+(n-1)T_0}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\sum_{i=1}^{n}\hat{\psi}_i\right), \qquad (11)$$

One then has

$$\hat{\psi}_{MODI}=\psi+\frac{1}{T_h-T_0}S_n^{-1}e. \qquad (12)$$

At this time, the average mean square deviation ε is

$$\varepsilon=\frac{1}{n}\sum_{i=1}^{n}\varepsilon_i=\left(\frac{1}{T_h-T_0}\right)^2\varepsilon_{\text{[illegible]}}. \qquad (13)$$

On the basis of Reference [6],

$$\varepsilon=\varepsilon_i=\frac{4}{n}\left(\frac{1}{T_h-T_0}\right)^2\sigma^2. \qquad (14)$$

The root mean square signal to noise ratio gain $\Delta(SNR)_{r.m.s.}$ is

$$\Delta(SNR)_{r.m.s.}=\left[\frac{E\{(\hat{\psi}_i-\psi_i)^2\}_{\text{没有多路传输}}^{(1)}}{E\{[(\hat{\psi}_{MODI})_i-\psi_i]^2\}_{\text{有多路传输}}}\right]^{1/2}_{(2)}=\frac{\sqrt{n}}{2}(T_h-T_0). \qquad (15)$$

(Key to Eq.(15): (1) Without Multichannel Transmission
(2) With Multichannel) Transmission

If one assumes that $T_h=1$ and $T_0=0$, then Φ_{modi}, ε, ε_i) as well as $\Delta(SNR)_{r.m.s.}$ given by equation (12), equation (13), as well as equation (15) are completely the same as the corresponding Φ, ε, ε_i, as well as for standard encoding masks associated with encoding matrix S_n.

3. CONCLUSIONS

(1) When utilizing LC-SLM to act as encoding masks, still according to standard encoding masks, one first carries out a quick Hagamard transform on measurement value vector η, obtaining spectrum estimate value vector (initial) $\hat{\psi}=S_n^{-1}\eta$. For specific calculation methods, consult reference [10]. After this, corrections are carried out on estimate value Φ. From equation (11), one obtains corrected spectrum estimate values Φ. These Φ are optimum estimate values for actual spectra.

(2) On the basis of the decoding method which we presented, we are able to deduce that, when LC-SLM act as HTS encoding masks, root mean square signal to noise ratio $\Delta(SNR)_{r.m.s.}=(\sqrt{n}/2)(T_h-T_0)$ It is possible to see that, compared to standard encoding masks, at this time $\Delta(SNR)_{r.m.s.}$ drops.

(3) Making use of equation (3) and equation (11), the authors carried out computer simulations, proving that the decoding methods given are accurate.

REFERENCES

[1] N. J. A. Sloane *et al.*, *Appl. Opt.*, 1969, **8** (10): 2103
[2] J. A. Decker *Jr. et al.*, *Appl. Opt.*, 1969, **8** (12): 2552
[3] P. G. Phillips, M. Harwit., *Appl. Opt.*, 1971, **10** (12): 2780
[4] M. Harwit, *Appl. Opt.*, 1971, **10** (8): 1415
[5] M. Harwit, *Appl. Opt.*, 1973, **12** (2): 285
[6] M. Harwit, N. J. A. Sloane, *Hahamard Transform Optics*. New York: Academic Press., **1979**
[7] D. C. Tilotta *et al.*, *Appl. Spectrosc.*, 1987, **41** (5): 727
[8] D. C. Tilotta *et al.*, *Appl. Spectrosc.*, 1987, **41** (8): 1280
[9] A. P. Bohlke *et al.*, *J. Mol. Structure* (*Thechem*), 1989, **200**: 471~481
[10] 张炳泉. *光学学报*, 1984, **4** (3): 229

DISTRIBUTION LIST

DISTRIBUTION DIRECT TO RECIPIENT

ORGANIZATION	MICROFICHE
B085 DIA/RTS-2FI	1
C509 BALLOC509 BALLISTIC RES LAB	1
C510 R&T LABS/AVEADCOM	1
C513 ARRADCOM	1
C535 AVRADCOM/TSARCOM	1
C539 TRASANA	1
Q592 FSTC	4
Q619 MSIC REDSTONE	1
Q008 NTIC	1
Q043 AFMIC-IS	1
E051 HQ USAF/INET	1
E404 AEDC/DOF	1
E408 AFWL	1
E410 AFDTC/IN	1
E429 SD/IND	1
P005 DOE/ISA/DDI	1
P050 CIA/OCR/ADD/SD	2
1051 AFIT/LDE	1
P090 NSA/CDB	1
2206 FSL	1

Microfiche Nbr: FTD95C000172
NAIC-ID(RS)T-0388-94