Optica Applicata, Vol. XXVI, No. 4, 1996

At the crossroads of nonlinear optics and Fourier optics

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The use of materials displaying nonlinear optical properties in devices based on Fourier optics, such as focusing systems, leads to a lot of new ideas mostly in the field of nonlinear image processing. This paper presents the principle of nonlinear filtering in a two lens set-up, and two applications, the first one to a method for nonlinear susceptibility measurements, the second one to information transfer from a wavelength to another through Raman scattering.

1. Nonlinear filtering in two lens set-up [1]–[3]

In the device described in Figure 1, the lens L_1 makes in its focal plane the Fourier transform $S(u,v)$ of the object $O(x,y)$. A nonlinear medium (NL) filters ($S(u,v)$ and transforms in into $S'(u,v)$. The lens L_2 provides the Fourier transform $O'(x,y)$ of $S'(u,v)$: $O'(x,y)$ is a filtered image of $O(x,y)$. In the absence of nonlinear medium $O'(x,y) \equiv O(x,y)$. Both the phase and amplitude of $S(u,v)$ can be changed by NL. If a Kerr medium is used, it displays a nonlinear refractive index change $\Delta n = n_2 I$, where $I = |S(u,v)|^2$ is the exciting intensity, and n_2 – the coefficient characterizing the Kerr effect. Thus the phase $\Delta\varphi = \frac{2\pi}{\lambda} l \Delta n$ (l – active length) is more changed in

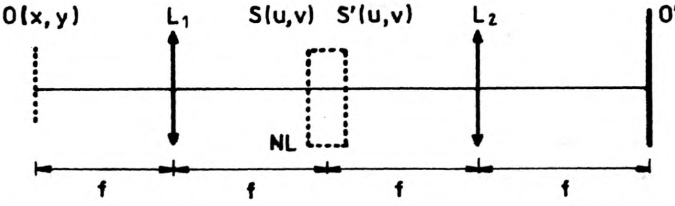
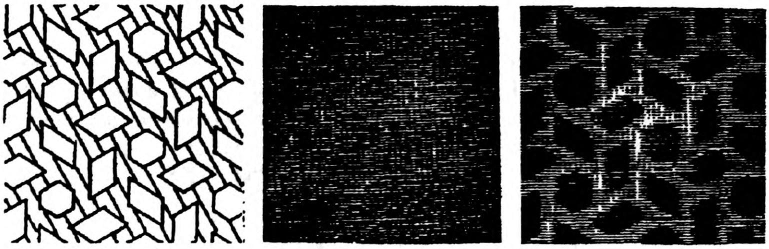


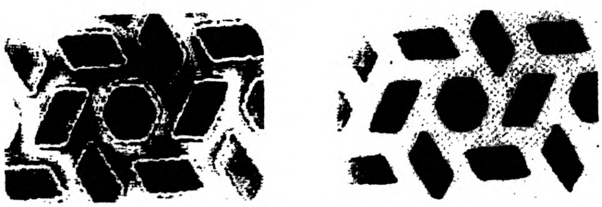
Fig. 1. Two lens set-up. $S(u,v)$ is Fourier spectrum of the object $O(x,y)$, $S'(u,v)$ is the spectrum $S(u,v)$ after filtering by the nonlinear material (NL), $O'(x,y)$ is the Fourier transform of $S(u,v)$

the intense components of the Fourier spectrum than in the weak components. If we consider, for instance, a quasi uniform object displaying small diffractive defects, the intense Fourier component due to the uniform part of the object will obey a large phase change while the lateral Fourier components due to the defects will be nearly unchanged. If this central phase change is π, the result will be the contrast reversal of the image, for an amplitude object, or the phase contrast imaging for a phase object. Of course, the image processing thus obtained can be produced with a linear screen (instead of NL) producing the same dephasing π between the Fourier components. The nonlinear method presents many advantages, whereas the linear screen has to be built especially, and aligned with a great lateral accuracy in the set-up (for instance, in the phase contrast microscope), the nonlinear filter is self-induced choosing the right intensity $|S(u,v)|^2$ in order to provide $\frac{2\pi}{\lambda} ln_2 |S(u,v)|^2 = \pi$ and does not need lateral alignments. It is (or can be) erased and re-built for each use.



a b c

2.1



b a

2.2

Fig. 2. Nonlinear image processing. 2.1. Phase contrast imaging (NL:$LiNbO_3$ crystal, laser:HeNe 1 mW), **a** — phase change in the object, **b** — image of the object without NL, **c** — image with NL. 2.2. Edge enhancement (NL:CS_2, laser:Nd YAG 25 ps), **b** — image of the object without NL, **c** — image with NL

If NL displays a nonlinear absorption, not only the phase but also the amplitudes of Fourier components of $S(u, v)$ undergo changes, leading to other image processing possibilities, such as edge enhancement. Figure 2 shows some examples of nonlinear image processing.

2. $\chi^{<3>}$ measurements by nonlinear image processing [4], [5]

The set-up presented in Figure 1 can be used to measure third order nonlinear susceptibilities. The principle is the next one: the object $O(x,y)$ being chosen and measured, its Fourier spectrum $S(u,v)$ is calculated. $S'(u,v)$ is calculated too, using the relation

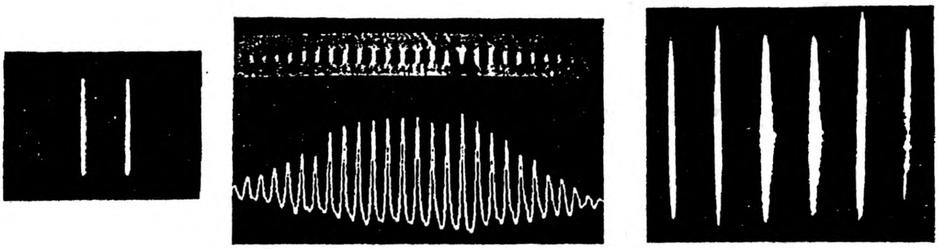
$$S'(u,v) = S(u,v)\,T(u,v)$$

with

$$T(u,v) = \frac{\exp(-\alpha l)}{1+\beta\dfrac{1-\exp(-2\alpha l)}{\alpha}|S(u,v|^2}\exp\left[\frac{in_2}{2\beta}\,\mathrm{Ln}\left(1+\beta\,\frac{1-\exp(-2\alpha l)}{\alpha}\,|S(u,v|^2\right)\right],$$

$T(u,v)$ is the transmission of NL, where α and β are respectively the coefficients describing linear and nonlinear absorption.

The Fourier transform $O'_c(x,y)$ of $S'(u,v)$ is calculated giving to n_2 and β (which are unknown) arbitrary values. The calculated intensity $O'_c O'^*_c(x,y)$ is compared to the measured one $O'_m O'^*_m(x,y)$, and the values of n_2 and β are varied till obtaining the adjustment $O'_c O'^*_c(x,y) \equiv O'_m O'^*_m(x,y)$. The experiment and simulation have been made, for instance, with and object made of two parallel slits. The Fourier spectrum is thus nearly sinusoidal, and the filtering results in additive lateral components in the image (Fig. 3). The intensity evolution in these lateral slits is easy to visualize and



a b c

Fig. 3. Image processing of a two-slit object for nonlinear susceptibility measurements (NL:$LiNbO_3$ crystal, laser: HeNe 1 mW). **a** — object $O(x,y)$, **b** — Fourier spectrum $S(u,v)$, **c** — $O'(x,y)$

measure. The method checked with reference liquids like CS_2, C_6H_6, $CHCl_3$, ..., and also with new organic materials [6], [7] proves to work.

Compared with other methods, the nonlinear image processing method presents many advantages: it is a one wave method that need only simple alignments (no longitudinal and lateral adjustments). One laser shot is sufficient in the case of pulse lasers. Neither laser spatial special shape (like Gaussian) nor stability are requested, since object and image are registered and compared in each shot. A simple look on the camera screen gives immediately a good idea of the order of $\chi^{<3>}$ by comparison with a reference material.

3. Raman imaging: image transfer from one wavelength to another

In the two lens device, if NL is a Raman active material, the Fourier spectrum $S(u,v)$ is transformed into a Raman spectrum $S_R(u,v)$. Either through the first lens L_1 for backward stimulated scattering, or through the lens L_2 for forward stimulated Raman scattering, the Fourier transform $O_R(x,y)$ of $S_R(u,v)$ is performed, leading to a Raman image. Can this image be replica of the object $O(x,y)$?

To obtain such a replica, two conditions are needed:

$$\begin{cases} |S_R(u,v)| \sim S(u,v), & (1) \\ \operatorname{Arg} S_R(u,v) = \operatorname{Arg} S(u,v) \quad (+C^{te}). & (2) \end{cases}$$

Condition (1) is not exactly realized, since the general relation between $|S_R|^2$ and $|S|^2$ is exponential ($|S_R|^2 \sim \exp(g|S|^2 l)$, where g is the Raman gain). The main problem will be the relative extinction of the weak components. However, the principal components in the laser spectrum will remain dominant in S_R. Condition (2) needs more attention: the initial phases in the spontaneously excited Raman modes have no relation with the laser phases [8]. Only the propagative Raman phase – due to diffraction – can have connections with the laser transverse shape and thus with the propagative laser shape. Thus the production of good replica of the object $O(x,y)$ in the Raman beam needs particular propagative conditions. Good results have been obtained using backward scattering and focusing the exciting beam strongly at the entrance of the Raman cell [9], [10]. In the forward scattering, the interest of such studies lies in the production of Raman beam transverse shapes controlled by laser beam shapes more than in the search of images. We note common features between the controlled distributed gain laser amplifiers [11] research and this work.

References

[1] PHU XUAN N., FERRIER J. L., GAZENGEL J., RIVOIRE G., BREKHOVSKHIKH G. L., KUDRIAVTSEVA A. D., SOKOLOVSKAIA A. I., TCHERNIEGA N., Opt. Commun. **68** (1988), 244.

[2] LI H. W., FERRIER J. L., GAZENGEL J., PHU XUAN N., RIVOIRE G., ZHANG J. J., Int. J. Optoelectron. **4** (1989), 533.

[3] LI H. W., FERRIER J. L., GAZENGEL J., PHU XUAN N., ZHANG J. J., RIVOIRE G., Opt. Commun. **76** (1990), 13.

[4] CHIS M., Doctoral Thesis, University of Angers, 1996, No. 418.

[5] BOUDEBS G., CHIS M., BOURDIN J. P., J. Opt. Soc. Am. B **13** (1996), 1450.

[6] SYLLA M., ZAREMBA J., CHEVALLIER R., RIVOIRE G., Synth. Metals **59** (1993), 111.

[7] SAHRAOUI B., SYLLA M., BOURDIN J. P., RIVOIRE G., ZAREMBA J., J. Mod. Opt. **42** (1995), 2095.

[8] VAUDELLE F., GAZENGEL J., RIVOIRE G., Opt. Commun., to be published in Dec. 1996.

[9] ER RHAIMINI S., LECOQ J. P., XUAN N. P., RIVOIRE G., TCHERNIEGA N., Opt. Commun. **104** (1993), 132.

[10] ER RHAIMINI S., VAUDELLE F., XUAN N. P., RIVOIRE G., TCHERNIEGA N., KUDRIAVTSEVA A. D., Proc. SPIE–ICONO 95, Vol. 2800, p. 286.

[11] DESFARGES A., KERMÈNE V., COLOMBEAU B., VAMPOUILLE M., FROEHLY C., Opt. Lett. **20** (1995), 1940.

Received, November 27, 1996