Author's Reply[2]

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I wish to extend my thanks to Ivakin, Lazaruk, Rubanov, and Stepanov for calling my attention to their work in real-time holograms and phase conjugation. Their early (1971) work (see Stepanov *et al.* [3] at the end of this note) constitutes a clear proposal and demonstration of phase conjugation by four-wave mixing. The time-reversed nature of the backward diffracted wave is fully appreciated and its distortion correction potential is manifested.

Not one of the thirty or so translated Russian papers, which I found in the field of four-wave conjugation and real-time holograms, all written after 1971, mentioned the pioneering work of Stepanov *et al.* I hope this note will help correct this situation.

I took advantage of this opportunity to sort out the chronology of key developments in this new field. In the process I became convinced that the distinction between phase conjugate optics and real-time holography is rather fuzzy. The latter term is more inclusive and can be used to describe the whole class of pictorial information processing experiments which utilize instantaneous or near instantaneous nonlinear optical response. The applications, almost always, involve a modification of the optical properties (the complex index of refraction) of the hologram medium by two incident optical beams and a simultaneous or slightly delayed scattering by the modified medium of a third wave. With this perspective in mind, I tried to trace again the evolution of basic ideas and key experiments in the field, as expressed through published reports. The list which follows contains comments meant to point out the main original contribution of each paper and relate it to previous work. The list is not meant to serve as a comprehensive bibliography and, of necessity, omits many worthwhile papers.

BIBLIOGRAPHY

[1] H. Boersch and H. Eichler "Beugung an einem mit stehnden lichtwellen gepumpten Rubin," *Z. Angew. Phys.*, vol. 22, p. 378, 1967 (Technical Univ. Berlin).

This seems to be the first description of Bragg scattering of a light beam from a grating produced by the standing wave interference of another light beam inside a material medium (in this case a ruby crystal). No holographic or image processing applications are considered. The main emphasis is on using the technique to measure relaxation times.

[2] H. J. Gerritsen, "Nonlinear effects in image formation," *Appl. Phys. Lett.*, vol. 10, p. 237, 1967 (RCA Labs.).

The first suggestion and demonstration of real-time holograms (the author calls them "temporary holograms"). The nonlinear medium is a saturable dye solution. The implications to "image processing" are recognized. Discussion is qualitative.

[3] B. I. Stepanov, E. V. Ivakin, and A. S. Rubanov, "Recording two-dimensional and three-dimensional dynamic holograms in transparent substances," *Sov. Phys.–Dokl.*, vol. 16, p. 46, July 1971, (submitted July 14, 1970) (Acad. Sciences, BSSR, Minsk).

The first suggestion and demonstration of wave conjugation and distortion correction by four-wave mixing. The discussion is qualitative.

[4] J. P. Woerdman, "Formation of a transient free carrier hologram in Si," *Opt. Commun.*, vol. 2, p. 212, 1970 (submitted July 23, 1970) (Phillips Research Labs., The Netherlands).

This paper, submitted nine days after [3]. contains a proposal and demonstration of a real-time hologram using the degenerate four-wave mixing geometry. The hologram is produced by a standing wave interference of an Nd^{3+}:YAG ($\lambda = 1.06\ \mu m$) beam inside a silicon crystal. The "time-reversed" nature of the backward diffracted wave is recognized and demonstrated in an imaging experiment. No analysis.

[5] D. L. Staebler and A. J. Amodei, "Coupled-wave analysis of holgraphic storage in $LiNbO_2$," *J. Appl. Phys.*, vol. 43, p. 1042, 1972 (RCA Labs).

This paper discusses the conditions (fringe shift) for energy exchange between waves in real-time holograms. This paper stimulated a great deal of Soviet works (and is often quoted) which are concerned with the possibility of transferring power from a distorted wave front to a planar wave.

[6] B. Y. Zeldovich, V. I. Popovichev, V. V. Ragulskii, and F. S. Faisulov, "Connection between the wavefronts of the reflected and exciting light in stimulated Mandel'shtam Brillouin scattering," *Sov. Phy. JETP*, vol. 15, p. 109, 1972 (Lebedev Inst., Moscow).

The first demonstration and explanation of phase conjugation and wavefront correction in a stimulated process. Authors were unaware of earlier work of Stepanov *et al.* [3].

[7] E. V. Ivakin, I. P. Petrovich, and A. S. Rubanov, "Self diffraction of radiation by light-induced phase gratings," *Sov. J. Quantum Electron.*, vol. 3, p. 52, July 1973 (Acad. Sciences, BSSR, Minsk).

First suggestion and demonstration of the use of real-time holograms for autocorrelation.

[8] Yu. A. Anan'ev, "Possibility of dynamic correction of wavefronts," *Sov. J. Quantum Electron.*, vol. 4, p. 929, Jan. 1975.

Author was unaware of [3]. Reinvents four-wave phase conjugation.

[9] Yu. I. Ostrovskii, V. G. Sidorovich, D. I. Stasel-ko, and L. V. Tanin, "Dynamic holograms in sodium vapor," *Sov. Tech. Phys. Lett.*, vol. 1, Nov. 1975.

The first suggestion and demonstration of the use of a resonantly enhanced transition, i.e., matching the wavelength to that of an atomic transition in the medium, in order to increase the efficiency of real-time holograms.

[10] A. Yariv, "On transmission and recovery of three-dimensional image information in optical waveguides," *J. Opt. Soc. Amer.*, vol. 66, p. 301, 1976 (California Inst. Technol., Pasadena, CA).

Proposal for use of three-wave (rather than four-wave) mixing in crystals for conjugate wave generation and for the use of conjugation to compensate for modal propagation dispersion. Use of nonlinear optical formalism to describe conjugation inside waveguides.

[11] J. P. Huignard and F. Micherson, "High sensitivity read-write volume holographic storage in $Bi_{12}SiO_{20}$ and $Bi_{12}GeO_{20}$ crystals," *Appl. Phys. Lett.*, vol. 29, Nov. 1976 (Thomson CSF, France).

Good example of the use of electronic quality crystals for real-time holography.

[12] R. W. Hellwarth, "Generation of time reversal wavefronts by nonlinear refraction," *J. Opt. Soc. Amer.*, vol. 67, p. 1, 1977 (Univ. S. California, Los Angeles, CA).

A proposal for generation of phase conjugate waves by the four-wave technique. Author was unaware of [3], which includes a similar proposal.

[13] A. Yariv and D. M. Pepper, "Amplified reflection, phase conjugation, and oscillation in dengenerate four-wave mixing," *Opt. Lett.*, vol. 1, p. 16, 1977 (California Inst. Technol., Pasadena, CA).

An application of the formalism of nonlinear optics to analyze degenerate four-wave mixing. Conjugate wave amplification and oscillation are predicted. Authors were unaware of [3].

[14] R. V. Avizonis, F. A. Hopf, W. D. Bamberger, S. F. Jacobs, A. Tomita, and K. H. Womack, "Optical phase conjugation in a $LinbO_3$ crystal," *Appl. Phys. Lett.*, vol. 31, p. 435, 1977 (Univ. Arizona, Tucson, AR).

Experimental demonstration of phase conjugation by three-wave mixing. The experiment confirms the basic inherent limitations of the technique, due to phase matching.

[15] V. Wang and C. R. Giuliano, "Correction of phase aberrations via stimulated Brillouin scattering," in *Proc. 1977 OSA Conf. on Laser Engineering and Applications*, Washington, DC, June 1977, paper 17.6; also in *Opt. Lett.*, vol. 2, p. 4, 1978 (Hughes Research Labs., Malibu, CA).

[2] Manuscript received February 12, 1979.

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First quantitative evaluation of the effectiveness of stimulated Brillouin scattering (see [6]) in wavefront correction.

[16] D. M. Bloom, P. F. Liao, and N. P. Economu, "Observation of amplified reflection by degenerate four-wave mixing in atomic sodium vapor," *Opt. Lett.*, vol. 2, p. 158, 1978 (Bell Labs., NJ).
The first observation of gain in phase conjugation. Confirmation of theoretical model [13].

[17] D. M. Pepper, D. Fekete, and A. Yariv, "Observation of amplified phase conjugate reflection and optical parametric oscillation by degenerate four-wave mixing in a transparent medium," *Appl. Phys. Lett.*, vol. 33, p. 1, 1978 (California Inst. Technol., Pasadena, CA).
Experimental confirmation of gain and oscillation [13] in the basic phase conjugation geometry.

[18] R. L. Abrams and R. C. Lind, "Degenerate four-wave mixing in absorbing media," *Opt. Lett.*, vol. 2, p. 94, 1978 (Hughes Research Labs., Malibu, CA).
A rigorous, coupled-mode analysis of four-wave phase conjugate mixing in a resonant two-level medium, which derives expressions for the mixing efficiency as a function of the atomic parameters, collision times and wave intensities.

[19] E. E. Bergmann, I. J. Bigio, B. J. Feldman, and R. A. Fisher, "High efficiency pulsed 10.6 m phase-conjugate reflection via degenerate four-wave mixing," *Opt. Lett.*, vol. 3, p. 83, 1978 (Los Alamos Labs.).
The first demonstration of phase conjugation in the infrared.

IR Laser Transition in a Nickel Hollow Cathode Discharge

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Abstract—**Laser oscillation in the infrared has been achieved in a nickel hollow cathode discharge. The 1.3968 μ laser transition is assigned to Ni I.**

Laser oscillation in nickel was first obtained at 1.454 μ by Chou and Cool [1]. The density of nickel atoms necessary for laser action was produced by dissociation of $Ni(CO)_4$ in the presence of helium.

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We have achieved quasi-CW laser action in a nickel hollow cathode at 1.3968 μ. The geometry of our hollow cathode was similar to that of Schubel [2]. The cathode was 50 cm long with a 2 mm × 6 mm slot along the length of it. The anode was made of tantalum mesh. The optics consisted of internally mounted high reflectivity mirrors. The buffer gas was helium with a small quantity of xenon. The optimum buffer gas pressure was 4–8 torr.

The metal vapor needed for laser action was produced by discharge sputtering. The discharge current pulsewidth was 100 μs and the pulse rate 40 Hz. The laser action occurred 30 μs after the end of the pulse and lasted 45 μs. The excitation mechanism seems to be electron-ion recombination in the afterglow [3]. The tabulated value of this Ni I transition is 1.3969 [4]. The current threshold was 18 A.

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[4] H. N. Russell, "Arc Spectrum of Nickel," *Phys. Rev.*, vol. 34, pp. 821–857, 1929.

Correction to "Spontaneous Emission Lifetime of the $C \rightarrow A$ Band of the XeF Molecule"

R. W. WAYNANT AND J. G. EDEN

In the above paper,[1] page 62, column 2, the abscissa title of Fig. 3 should read "p_{XeF_2} (torr).

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[1] R. W. Waynant and J. G. Eden, *IEEE J. Quantum Electron.*, vol. QE-15, pp. 61–63, Feb. 1979.

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