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Second Winter College on Optics

20 February - 10 March 1995

Photorefractive Effect and Applications Part III

K. Singh

Indian Institute of Technology
Department of Physics
New Delhi, India

MAIN BUILDING STRADA COSTIERA, 11 TEL. 2240111 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449
MICROPROCESSOR LAB. VIA BEIRUT, 31 TEL. 224471 TELEFAX 224600 TELEX 460392 GALILEO GUEST HOUSE VIA BEIRUT, 7 TEL. 22401 TELEFAX 2240310 TELEX 460392

SECOND WINTER COLLEGE ON OPTICS
ICTP, TRIESTE (ITALY); 20 FEB–10 MARCH 1995

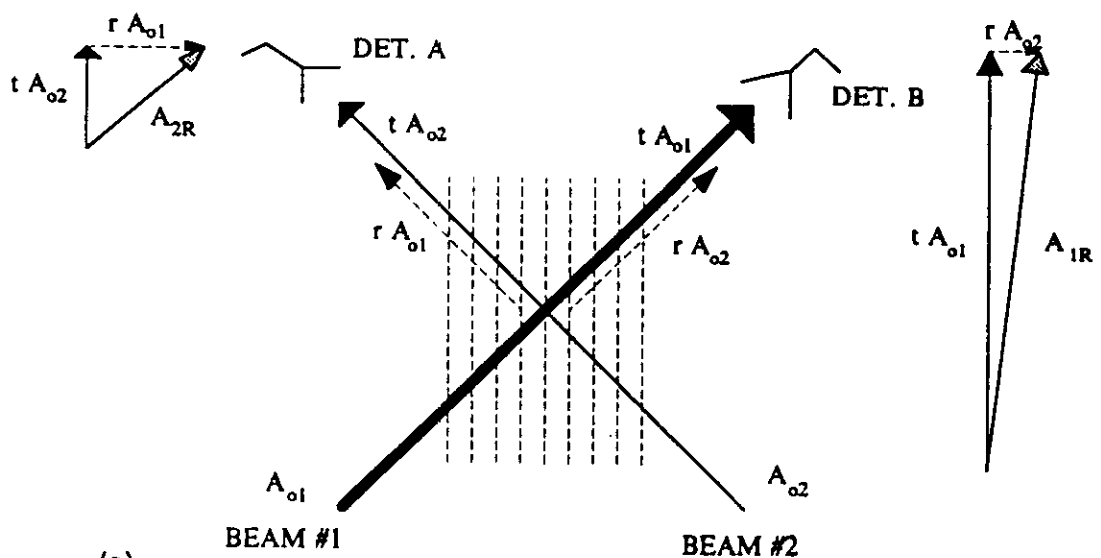
PHOTOREFRACTIVE EFFECT, MATERIALS AND APPLICATIONS

KEHAR SINGH

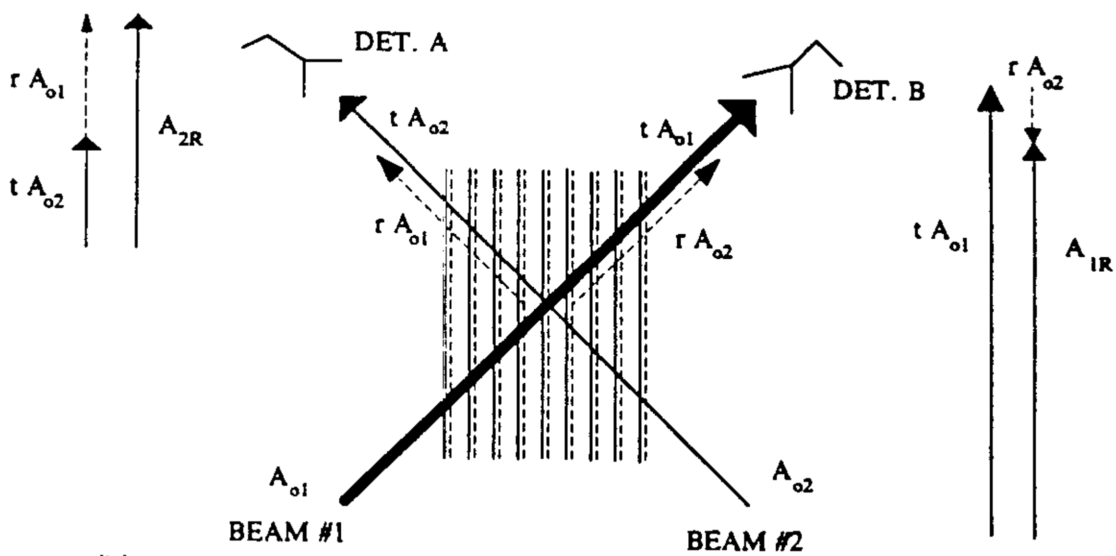
PHOTONICS GROUP, PHYSICS DEPARTMENT
INDIAN INSTITUTE OF TECHNOLOGY
HAUZ KHAS, DELHI, NEW-DELHI 110016
INDIA

FAX: 91-11-6862037
TELEX: 31-73087 IITD IN
31-61460 IITD IN
e-mail: kehars @ physics.iitd.ernet.in

LIGHT ACTS ON THE MATERIAL;
MATERIAL ACTS BACK ON THE LIGHT.



(a)



(b)

Figure The energy transfer mechanism: (a) the index grating and the intensity grating are in phase; (b) the index grating is $\pi/2$ out-of-phase with the intensity grating.

VOLUME NATURE OF THICK HOLOGRAM

↓ PERMITS

INTERFERENCE OF INCIDENT BEAM WITH ITS OWN DIFFRACTED BEAM INSIDE MEDIUM.

SO → CONTINUOUS RECORDING OF NEW GRATING;

NON UNIFORM THROUGH THICKNESS.

MAY BE PHASE SHIFTED W.r.t. INITIAL GRATING

MAY INTERFERE CONSTR. OR DESTR. WITH IT

PHASE SHIFT (BETWEEN FRINGE PATTERN & RECORDED GRATING) → DYNAMIC ENERGY REDISTRIBUTION BETWEEN TWO BEAMS.

THIS SELF-DIFFRACTION EXISTS BECAUSE WRITING & READING OCCURS SIMULTANEOUSLY.

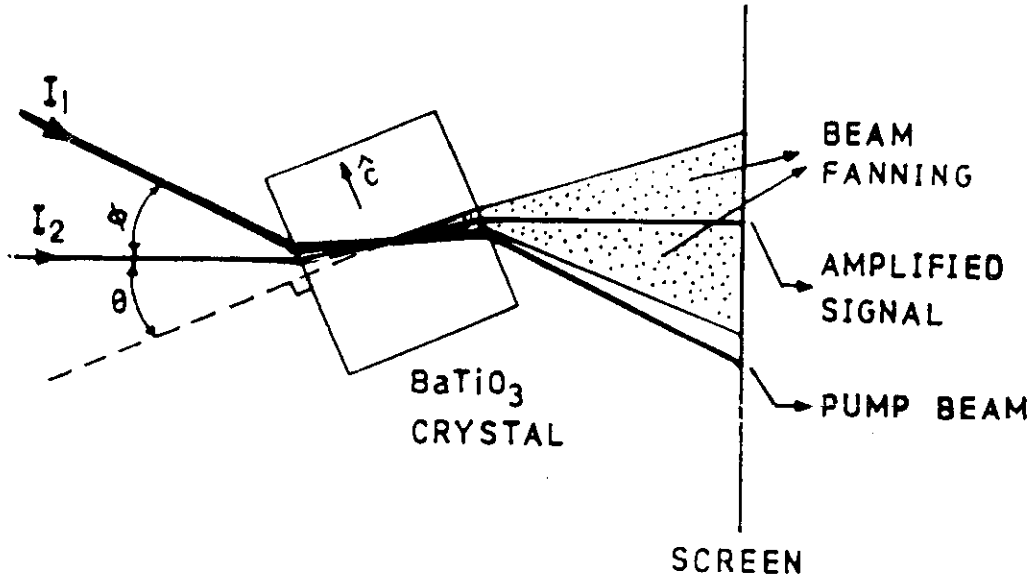
TRANSIENT DYNAMIC SELF DIFFRACTION IN ELECTRO-OPT. CRYSTALS ANALOGOUS TO NON-LINEAR OPT. EFFECTS (SELF-FOCUSING, SELF-DEFOCUSING, STIMULATED SCATTERING ETC & OTHER INTERACTIONS IN MEDIA WITH NON LINEAR POLARIZABILITIES.)

DIFFERENCE → Non-Linear Ref. index change

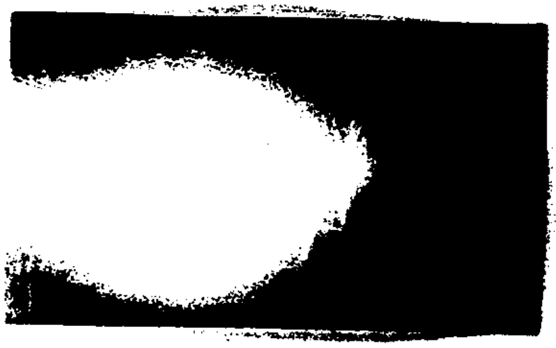
↓

ELECTRONIC ORIGIN

PHOTOREFR → Electro Opt Effect - Space charge



(a)



(b)

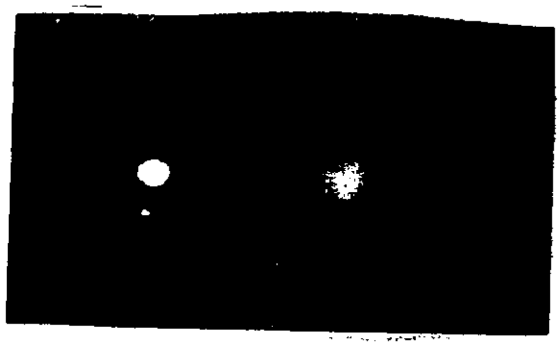
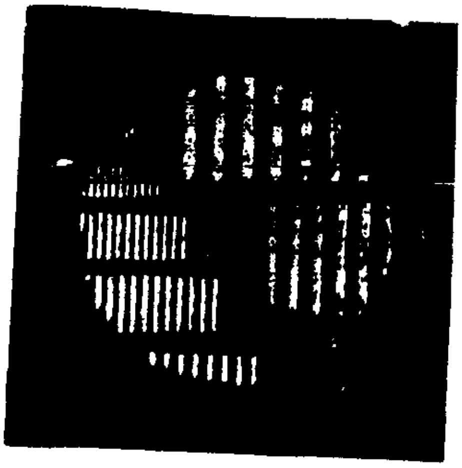


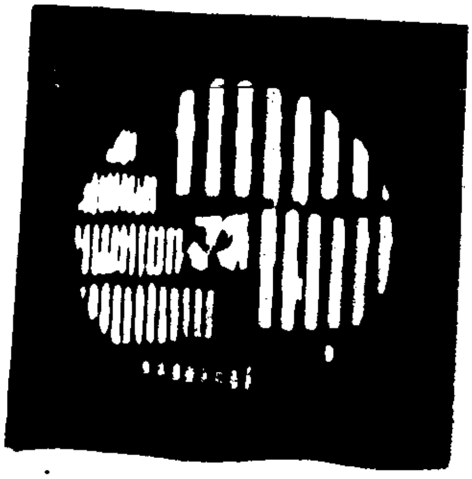
IMAGE AMPLIFICATION

(Joseph, Pillai and Singh, Opt. Commun. 80 (1990) 84]

(a)



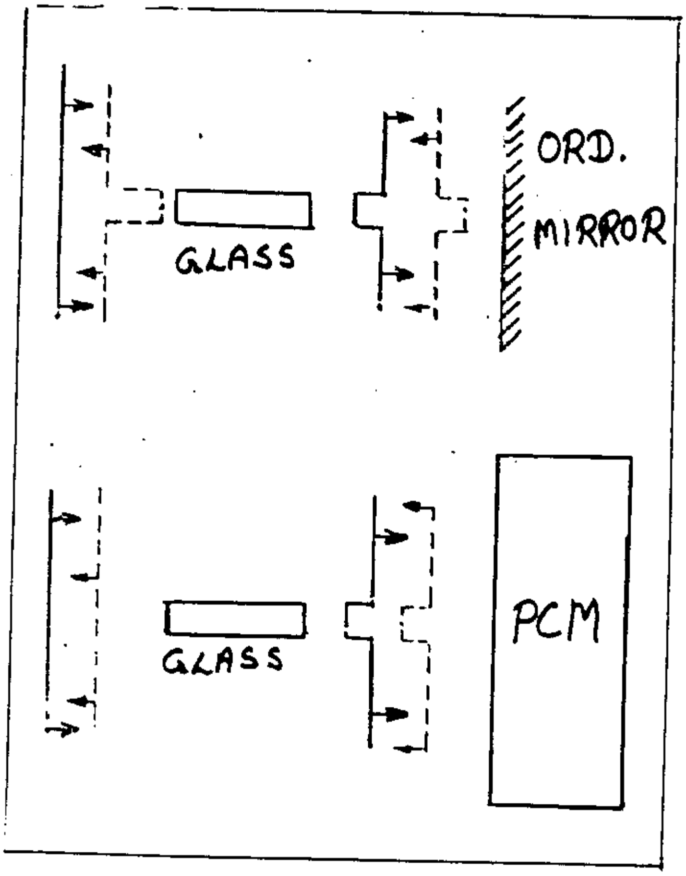
(b)

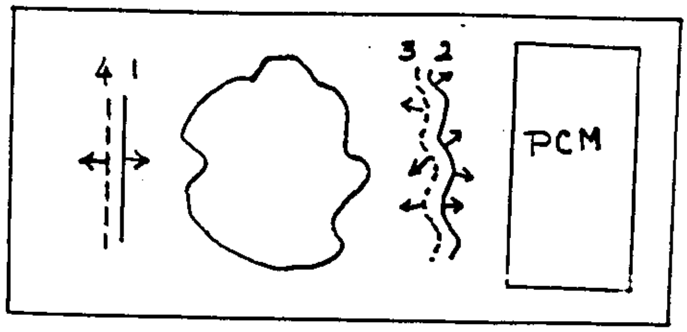


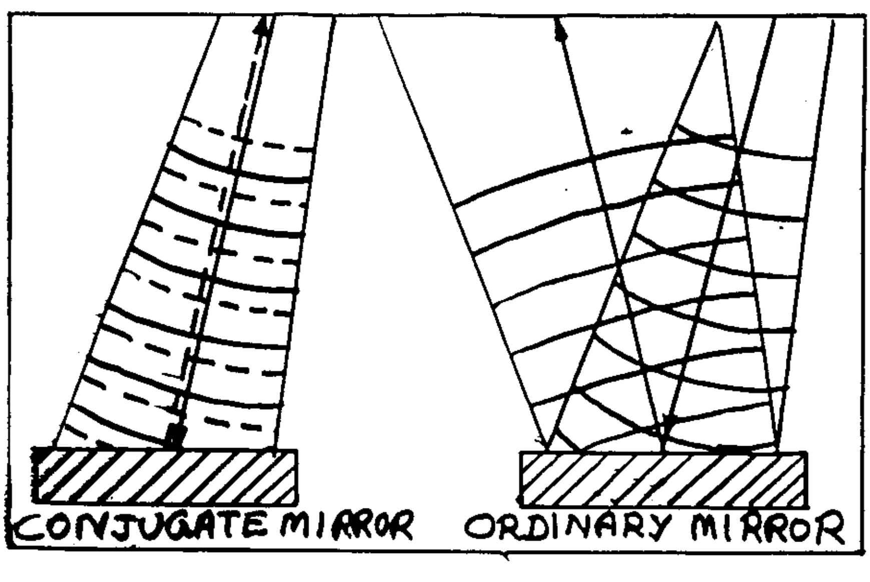
BEAM-FANNING
REDUCED

(c)

[JOSEPH, PILLAI AND SINGH, Opt. Commun 80(1990)84]


ORD.
MIRROR
GLASS
GLASS
PCM


4 1
3 2
PCM


CONJUGATE MIRROR
ORDINARY MIRROR

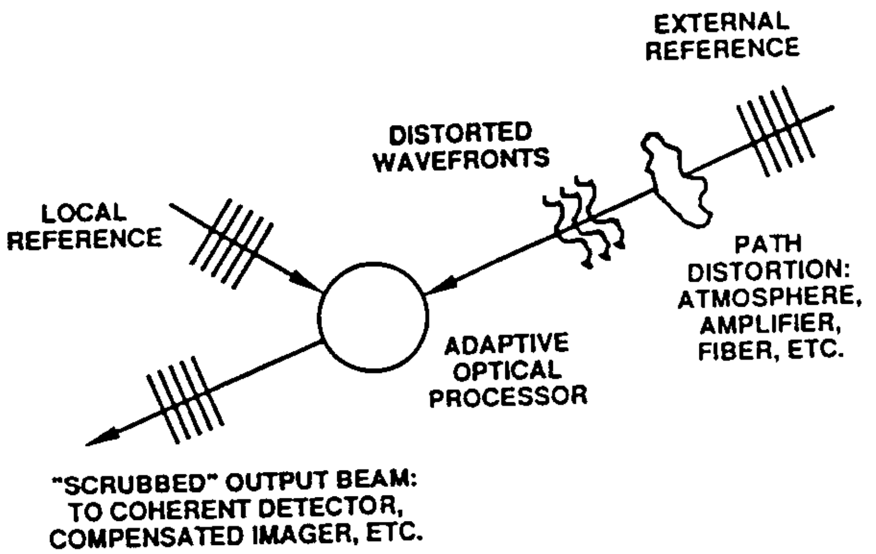


Figure Adaptive optical flowchart for the so-called receiver mode. In this case, the system drives the wave front of an input beam to that of a local reference wave, which is typically a plane wave or a focused beam.

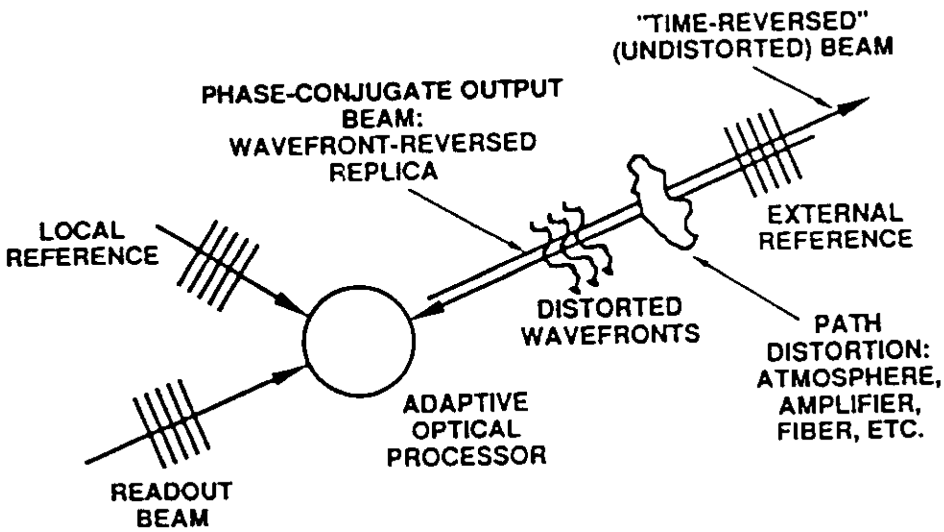
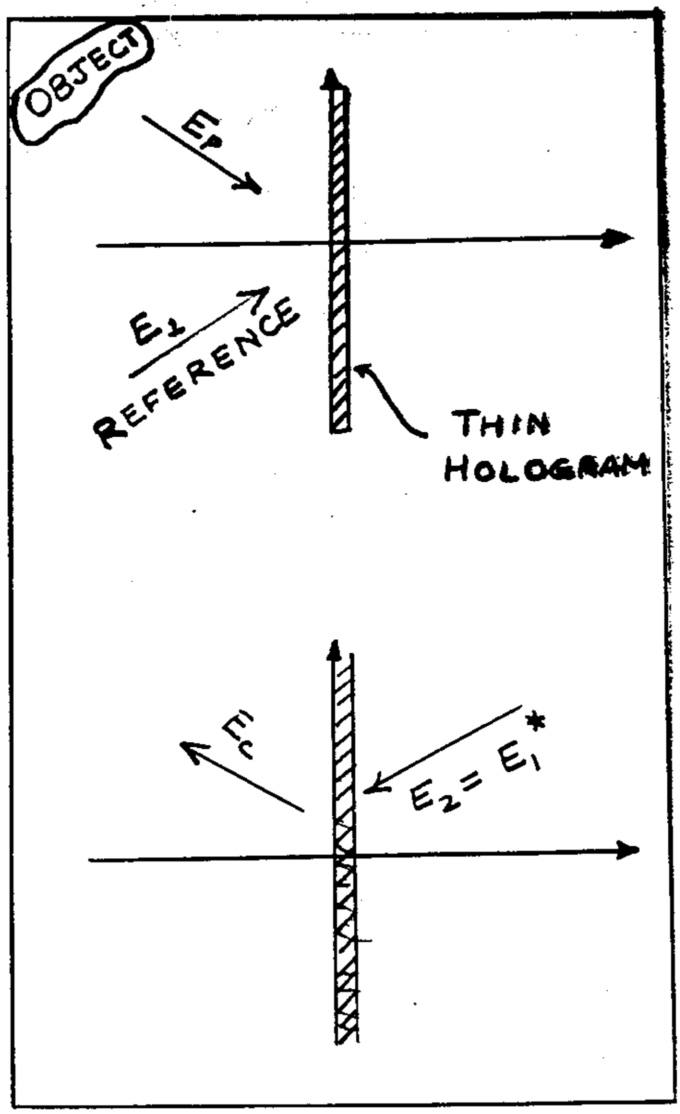


Figure Adaptive optical flowchart for the so-called transmission mode. In this case, the system can be used to generate an output beam, whose wave front propagates in a "time-reversed" manner relative to the input external reference beam.



RECORDING:

$$\left(A_0 e^{i\phi_0} + A_R e^{i\phi_R}\right)\left(A_0 e^{-i\phi_0} + A_R e^{-i\phi_R}\right)$$

$$= A_0^2 + A_R^2 + A_0 A_R\, e^{i\phi_0} e^{-i\phi_R} + A_0 A_R\, e^{-i\phi_0} e^{i\phi_R}$$

RECONSTRUCTION:

$$A_R e^{i\phi_R} \left(A_0 A_R^2 e^{i\phi_0} + A_0 A_R^2 e^{2i\phi_R} e^{-i\phi_0} \right)$$

ORTHOSCOPIC

PHASE CONJ.
PSEUDOSCOPIC

CONCAVE $\rightleftharpoons$ CONVEX

TIME-REVERSAL :

OPTICAL WAVE of FREQ. ω MOVING IN $+z$ DIRECTION

$$E = \mathrm{Re}\left[\psi(x,y,z)\, e^{i\omega t}\right]$$

Where, $$\psi(x,y,z) = A(x,y)\, e^{i(-kz + \phi(x,y))}$$

A real

P.C. OF E

$$E_{pc} = \mathrm{Re}\left[\psi^*(x,y,z)\, e^{i\omega t}\right]$$

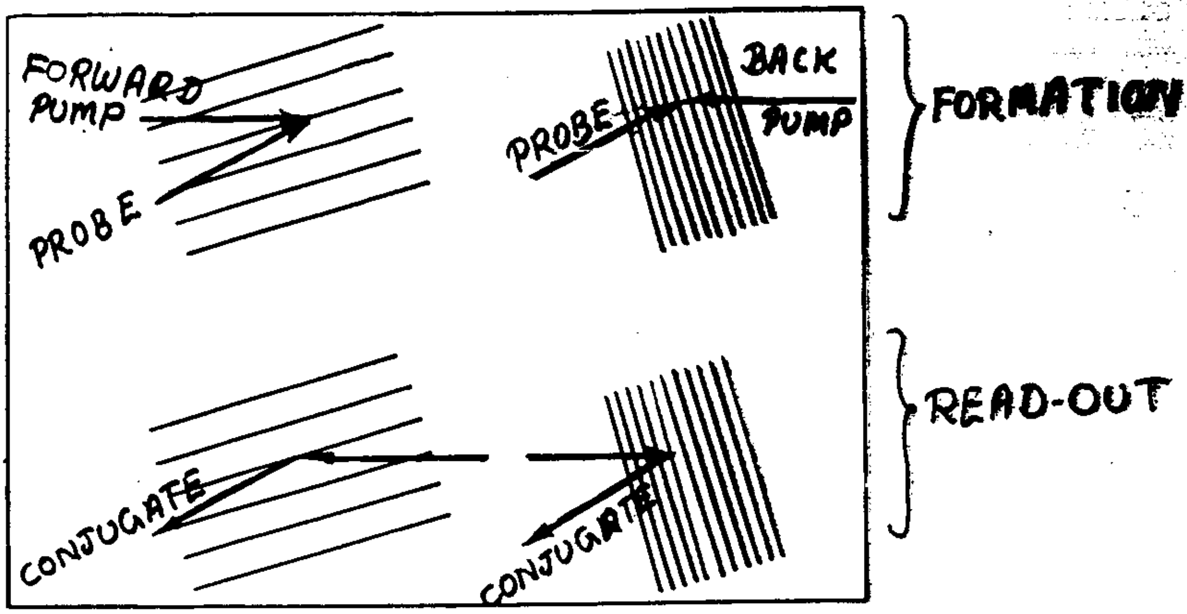
$$= \mathrm{Re}\left[A(x,y)\, e^{i(kz - \phi(x,y))}\, e^{i\omega t}\right]$$

CONTAINS THE COMPLEX CONJUGATE OF ONLY SPATIAL PART, LEAVING TEMPORAL PART UNCHANGED.

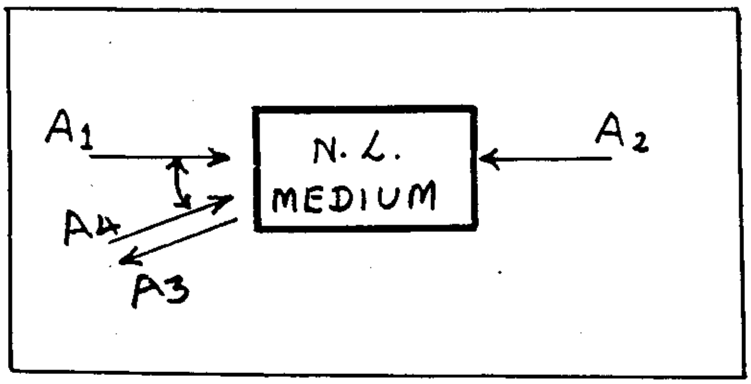
CORRESPONDS TO WAVE MOVING IN $-z$ DIRECTION, WITH PHASE $\phi(x,y)$ REVERSED RELATIVE TO INCIDENT WAVE.

TYPE OF REFLECTION COMBINED WITH PHASE REVERSAL. EQUIVALENT TO LEAVING SPATIAL PART OF E UNCHANGED AND REVERSING SIGN OF t. THUS EQUIVALENT TO

TIME REVERSAL

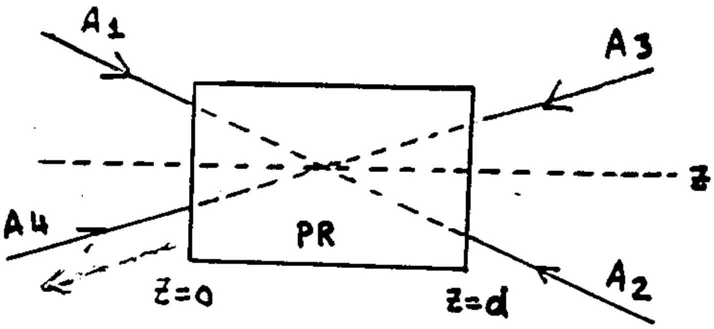


AN EXPERIMENT WITH PHOTOREFRACTIVE MATERIAL IS LIKE AN ARRANGED MARRIAGE: WE HOPE IT WILL BE INTERESTING AND OFTEN WE ARE PLEASANTLY SURPRISED.



EXPERIMENTING WITH A P.R. CRYSTAL MAKES ONE FEEL LIKE A YOUNG CHILD EXAMINING A CATERPILLAR: IF I POKE IT HERE WHAT WILL IT DO?

MULTIGRATING PHASE CONJUGATION VIA DFWM IN PHOTOREFRACTIVE CRYSTALS



$d \Rightarrow$ THICKNESS
$A_1 \Rightarrow$ FORWARD PUMP
$A_2 \Rightarrow$ BACKWORD PUMP
$A_3 \Rightarrow$ PHASE CONJUGATE (PC)
$A_4 \Rightarrow$ SIGNAL

FOUR DIFFERENT TYPES OF GRATINGS IN A STANDARD DFWM GEOMETRY

SINGLE GRATING $\Rightarrow$ APPROPRIATE CHOICE OF
- POLARIZATION
- COHERENCY
- ORIENTATION OF THE CRYSTAL

(1) TRANSMISSION TYPE (T)
MIXING OF A_4 WITH A_1; AND A_2 WITH A_3
$\Rightarrow A_T = A_1 A_4^* + A_2^* A_3$

(2) REFLECTION TYPE (R)
MIXING OF A_4 WITH A_2 AND A_3 WITH A_1
$\Rightarrow A_R = A_2^* A_4 + A_1 A_3^*$

(3) MIXING OF TWO PUMS $\Rightarrow A_1$ AND A_2
$\Rightarrow A_P = A_1 A_2^*$

(4) MIXING OF SIGNAL AND ITS CONJUGATE
$\Rightarrow A_S = A_3 A_4^*$

A_T, A_R, A_P & $A_S \longrightarrow$ INTERFERENCE TERMS

NUMERICAL MODELING OF PHOTOREFRACTIVE TWO-WAVE AND FOUR-WAVE MIXING

T.K. DAS, Ph.D. THESIS* (1991)

- INTENSITY DEPENDENT COUPLING IN TWM
- SYMMETRIC AND ASYMMETRIC CONFIGURATION DURING DFWM
- PHASE CONJUGATION THROUGH MULTIPLE GRATINGS IN DFWM
- VARIOUS METHODS TO SOLVE DFWM EQUATIONS
- MULTISTABILITY IN PHASE CONJUGATION WITH REFLECTION TYPE DFWM

* IIT DELHI

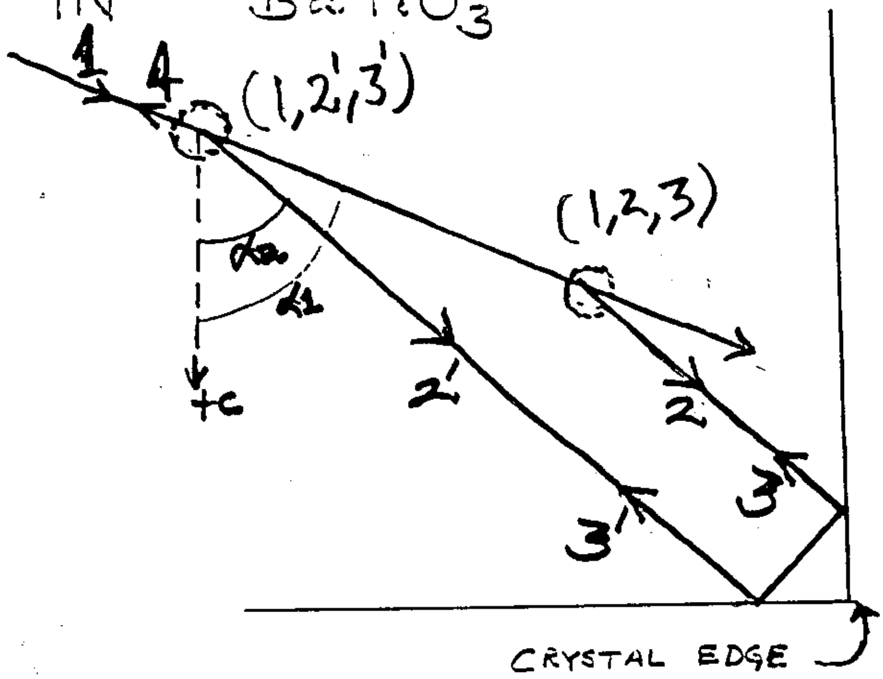
CROSS AND PARALLEL POLARIZATION COUPLING AND HIGHER-ORDER SELF-DIFFRACTION; TWM AND DFWM

AMITAVA ROY, Ph.D. THESIS* (1992)

- CROSS POLARIZATION COUPLING IN TWM
- CROSS POLARIZATION COUPLING IN DFWM
- CROSS & PARALLEL POLARIZATION COUPLING IN TWM AND DFWM
- CRYSTAL ORIENTATION DEPENDENT CROSS AND PARALLEL POLARIZATION COUPLING
- HIGHER-ORDER SELF-DIFFRACTION WITH OPTICAL ACTIVITY
- HIGHER-ORDER SELF-DIFFRACTION WITH ARBITRARY PHASE SHIFT

* I.I.T. DELHI

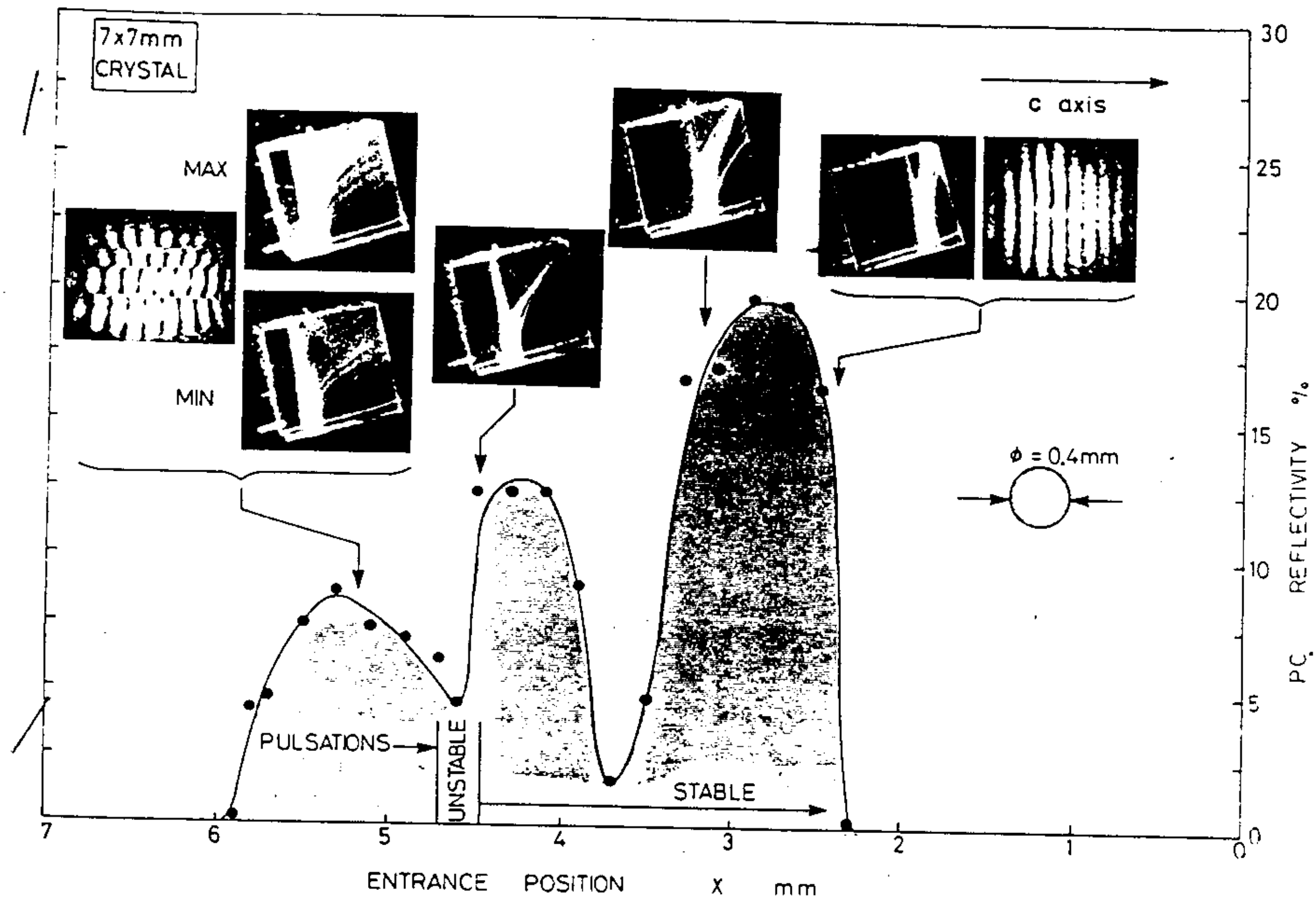
SELF-PUMPED PHASE CONJUGATION IN $BaTiO_3$



- 1 ENTERS , 2 SPLITTS OFF , TWICE TIR AT CRYSTAL EDGE AND BECOMES 3', INTERSECTS 1. 2' SPLITTS OFF FROM 1, TRAVELS ROUND THE LOOP TO GIVE 3.
- BEAMS 1, 2 & 3 GENERATE 4 BY FWM. AS DO BEAMS 1, 2' & 3'.

FERROELECTRIC WITH TETRAGONAL SYMMETRY C_{4v} BETWEEN 5°C AND 133°C.

LONG WORKING
$BaTiO_3$ → MANY THOUSAND OF HOURS OVER 9 YEARS IN Ar^+ BEAM



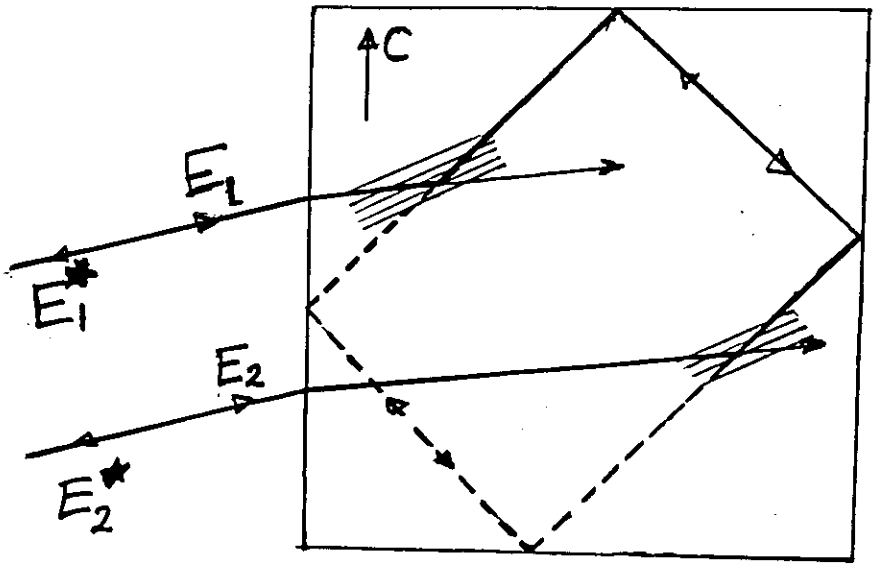
1988

ROLE OF IRON IMPURITY CENTERS

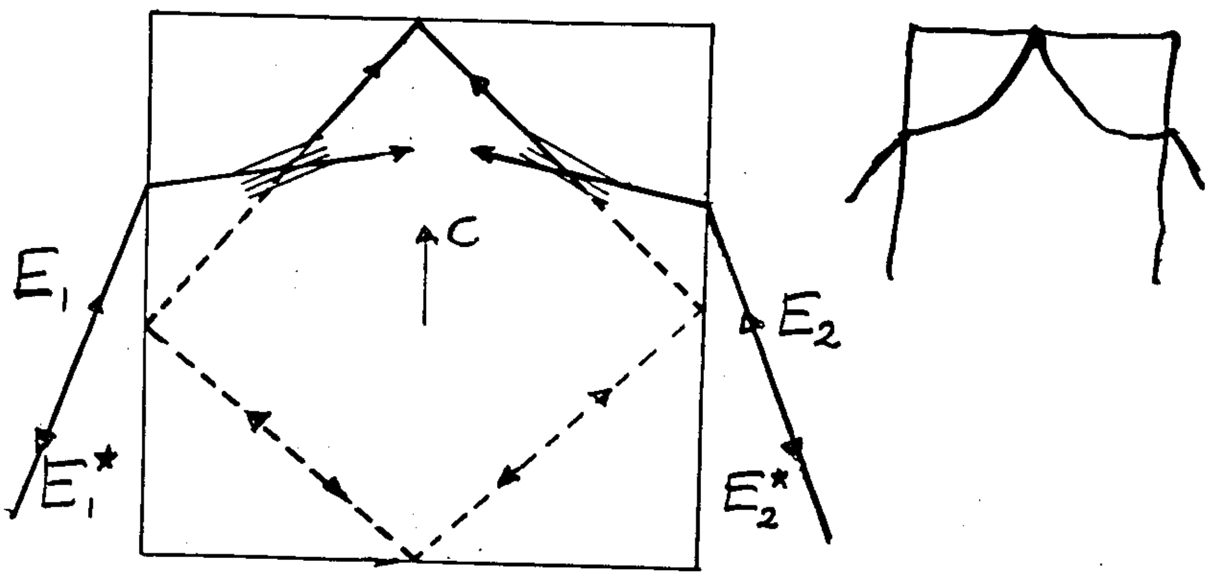
ACTIVE IMPURITY LEVELS OF Fe, Cr, & Mn

EFFECT OF FEED MATERIAL & ANNEALING ATMOSPHERE
(CONTROLLED - OXYGEN PARTIAL PRESSURE)

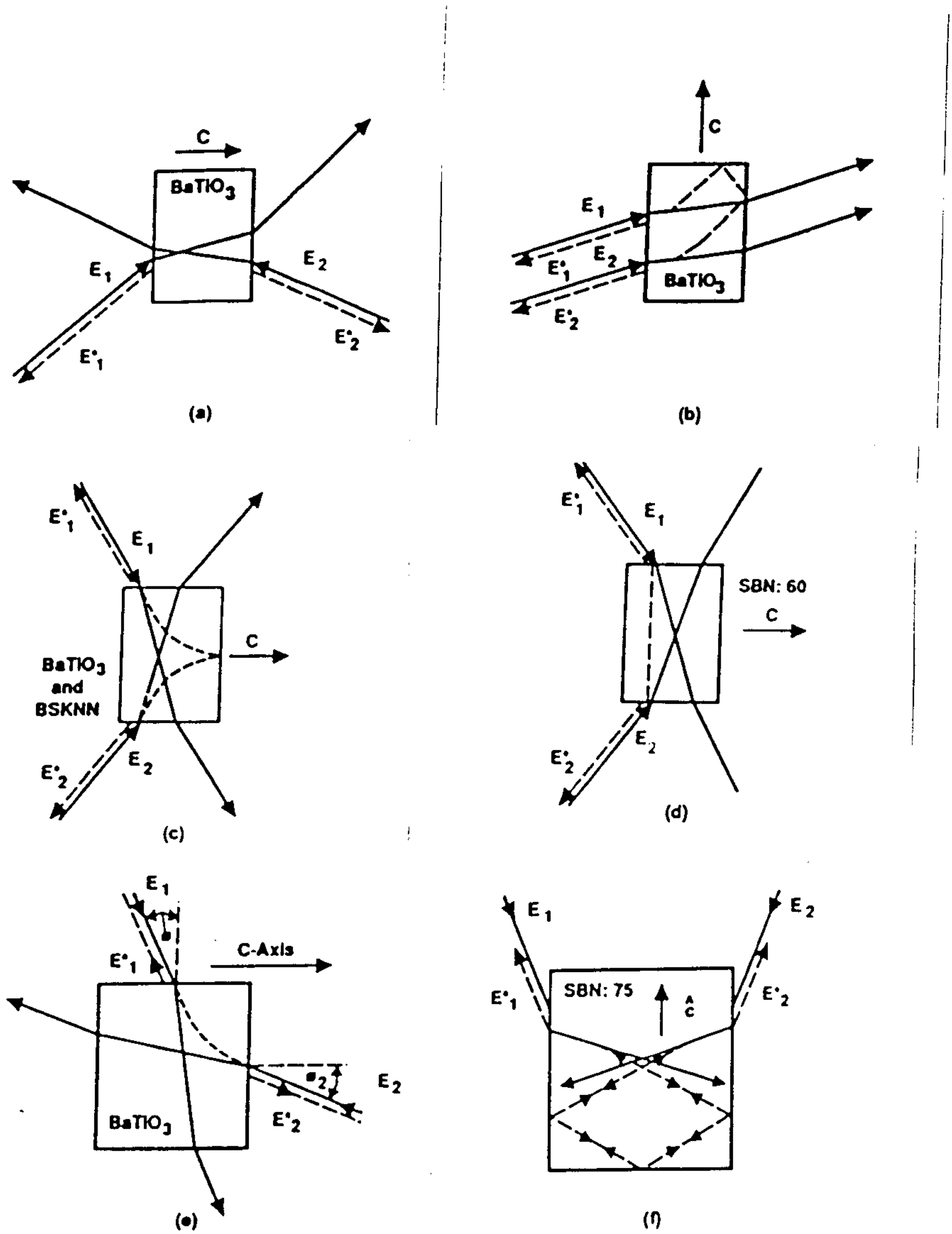
1989:
SBN : Rh ; Nanosecond pulses; self-phase Conj
IMP : Fe ;
$KNbO_3$



(a) MUTUALLY INCOHERENT BEAM COUPLER



(b) BIRD-WING PHASE CONJUGATOR



Geometries which have been employed to observe double phase conjugation (DPC). (a) The first reported observation of DPC (~~Ref. 23~~); (b) the mutually incoherent beam coupler (~~Ref. 24~~); (c) the bird-wing configuration using total internal reflection from one surface (~~Ref. 110~~); (d) the bridge conjugator (~~Ref. 109~~); (e) a modified bridge conjugator using a 45° $BaTiO_3$ configuration (~~Refs. 109 and 112~~); and (f) the frog-legs configuration using total internal reflection from three surfaces (~~Ref. 11~~)

APPLICATIONS (Contd.)

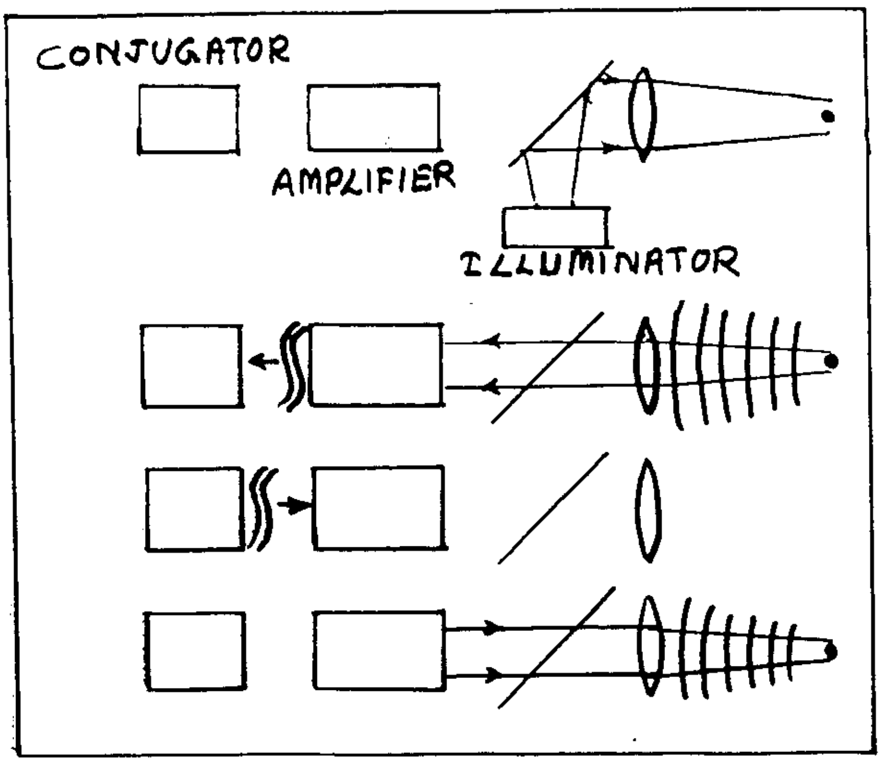
ADAPTIVE OPTICS FOR LASER FUSION

a. ILLUMINATION OF PELLET WITH PROBE BEAM

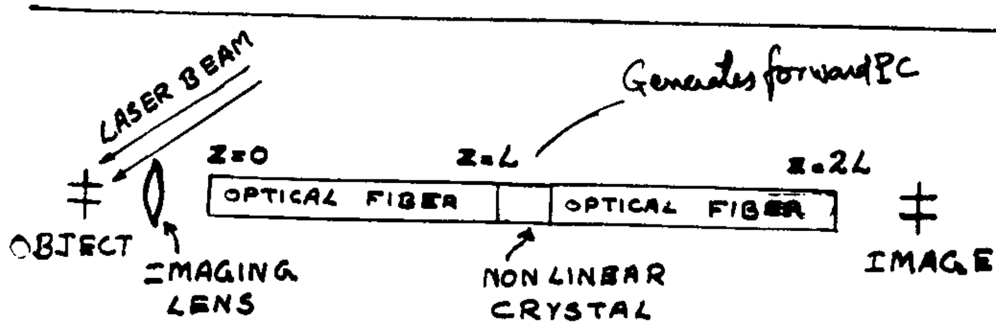
b. REFLECTION + AMPLIFICATION, RESULTING IN DISTORTED WAVE

c. CONJUGATION

d. SECOND PASS THROUGH DISTORTING MEDIUM PRODUCING COHERENT ILLUMINATION OF PELLET.

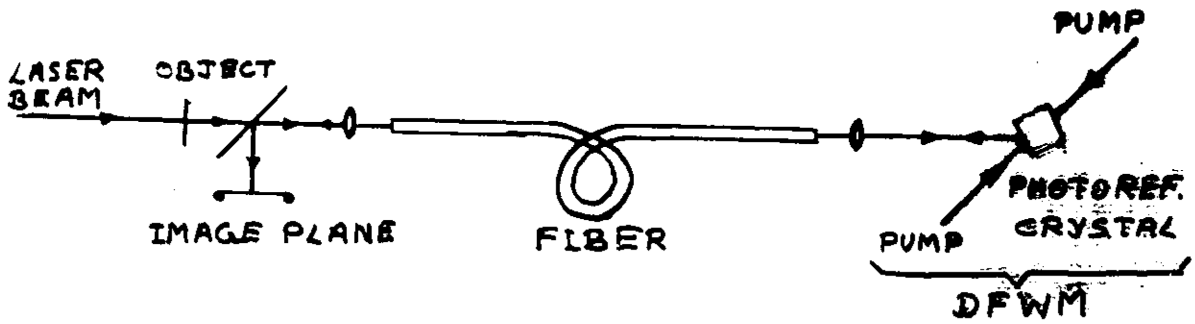


3D PICTORIAL TRANSMISSION IN OPTICAL FIBERS USING PHASE CONJUGATION



- AT z=L SMEARED PICTURE O/p DUE TO FIBER MODAL NOISE
- IMAGE RESTORATION DUE TO MODAL PHASE COMPENSATION BY PHASE CONJUGATION

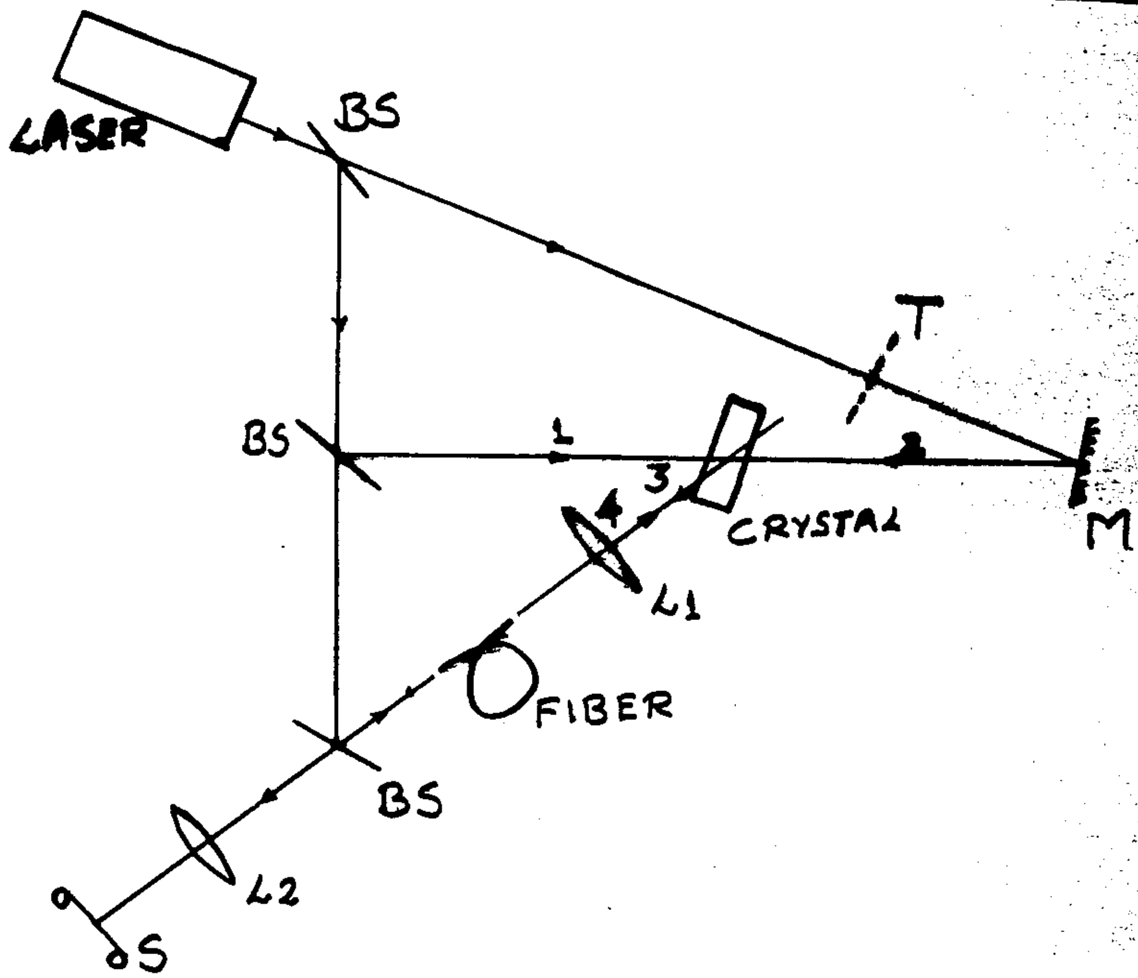
TWO-WAY IMAGING



- OBJECT & IMAGE AT i/p END OF THE FIBER
- DFWM CAN BE REPLACED BY SELF PUMPED PHASE CONJUGATION (Ex: IN $BaTiO_3$)

SCHEMES FOR 'THICK' DISTORTERS ALSO

ONE-WAY IMAGING USING FWM



PLANE-WAVE BEAM 4 IS DISTORTED BY FIBER,

$A_4(r) = A_{40} e^{i\phi(r)}$

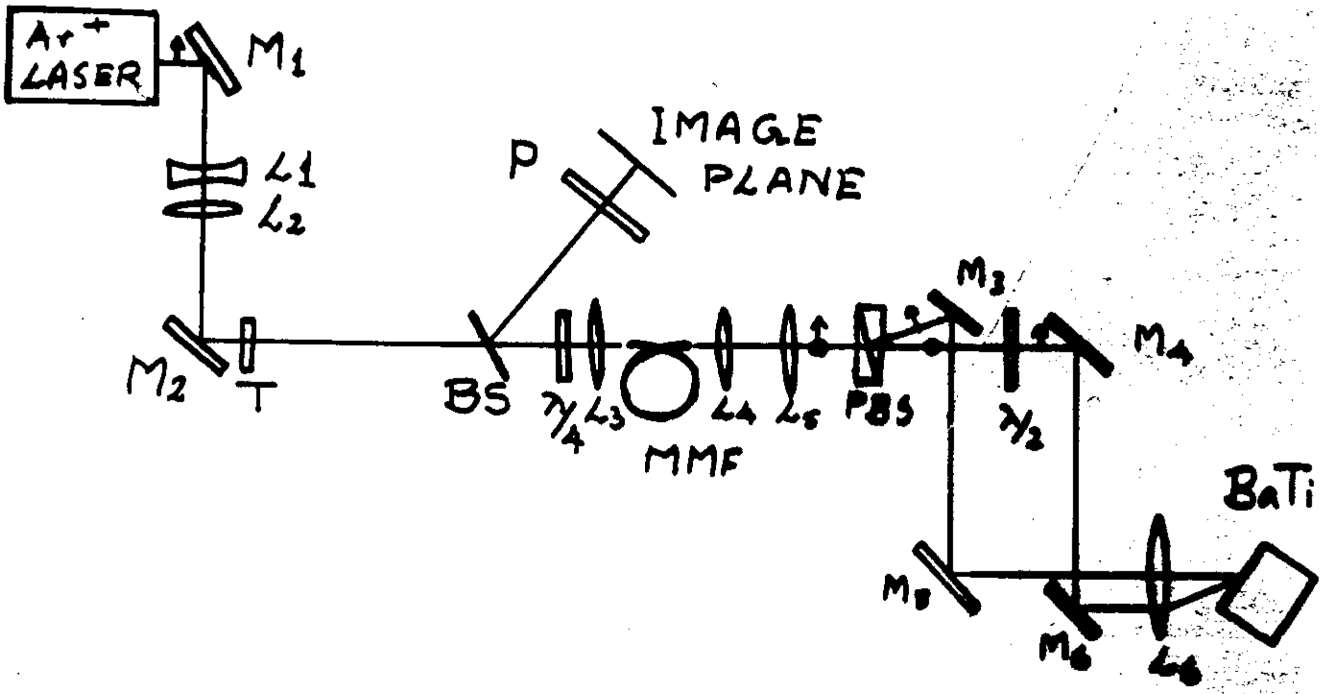
FWM PRODUCES BEAM 3, $A_3(r) \propto A_1 A_2(r) A_4^*(r) = A_1 A_2(r) A_{40}^* e^{-i\phi}$

THUS DISTORTION'S PHASE FACTOR IS CONJUGATED

BEAM 3 PASSES THROUGH FIBER,

$$\underline{A_3'(r) = A_3(r) e^{i\phi(r)} \propto A_1 A_2(r) A_{40}^*}$$

THE DISTORTION IS CANCELLED OUT AND A_3 IS LEFT WITH PICTORIAL FIELD INFORMATION A_2



- IMAGE RESTORATION BY POLARIZATIC PRESERVING PHASE CONJUGATION (PPPC)

- CONTRAST OF THE ORIGINAL IMAGE IS RESTORED ONLY WHEN PC PRESERVE POLARIZATION ON REFLECTION

RESOLUTION CHART

GREYSCALE GRID

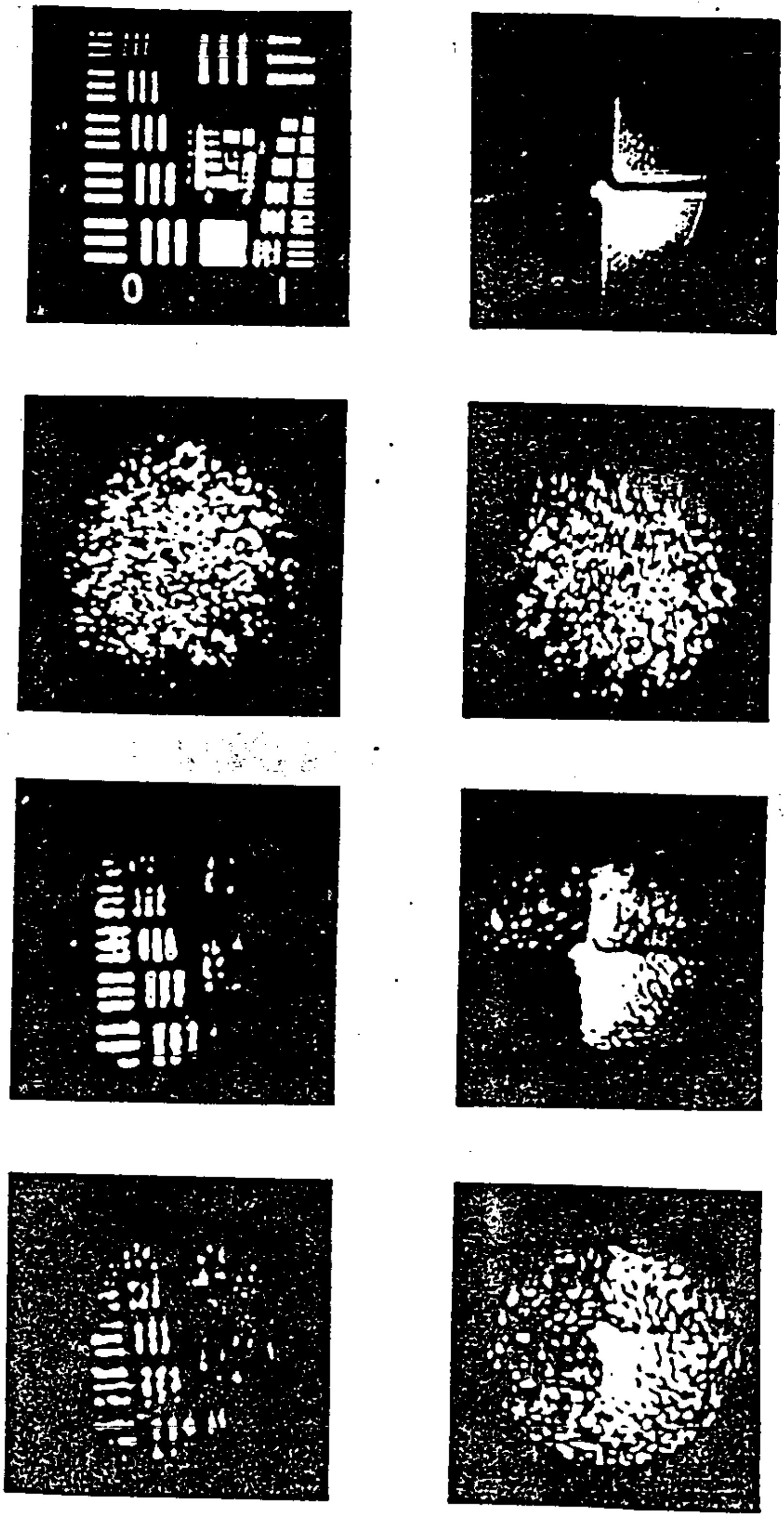
INPUT IMAGE PATTERN

SINGLE-PASS FIBER OUTPUT

DOUBLE-PASS FIBER OUTPUT

POLARIZATION PRESERVING PHASE-CONJUGATE MIRROR

PHASE-CONJUGATE MIRROR (NONPOLARIZATION PRESERVING)



Rockwell International
Science Center

REAL-TIME IMAGE PROCESSING USING PHOTOREFRACTIVE NON-LINEAR WAVE-MIXING IN $BaTiO_3$ AND BGO CRYSTALS

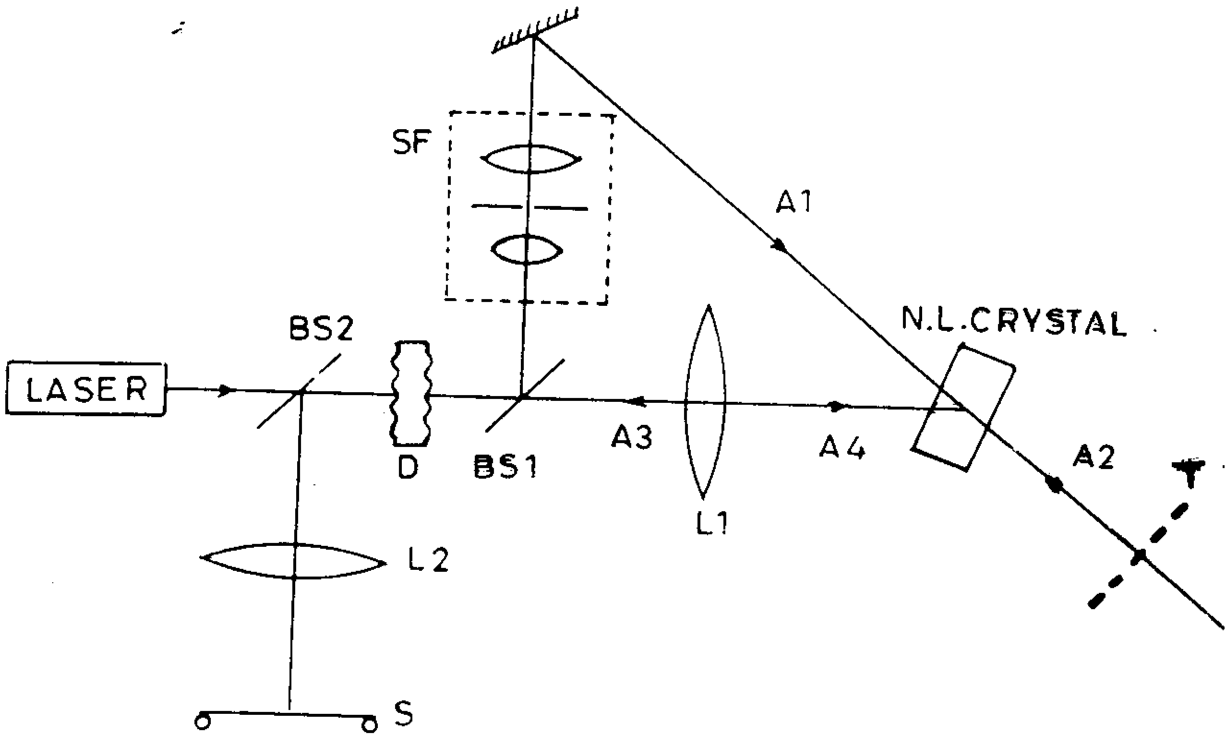
*

[Ph.D. THESIS, J. JOSEPH; 1992]

- SIGNAL BEAM AMPLIFICATION VIA TWO-BEAM COUPLING IN PR $BaTiO_3$
- ANISOTROPIC CONICAL SCATTERING IN PR $BaTiO_3$
- PULSE READ-OUT SCHEME FOR NOISE-FREE IMAGE AMPLIFICATION VIA TWO-BEAM COUPLING IN $BaTiO_3$
- SPATIAL AMPLIFICATION VIA SELECTIVE ERASURE : REAL-TIME IMAGE PROCESSING TECHNIQUE
- PHASE CONJUGATE ONE-WAY SCHEME FOR IMAGING THROUGH PHASE DISTORTION

* I.I.T. DELHI

ONE-WAY IMAGING SCHEME



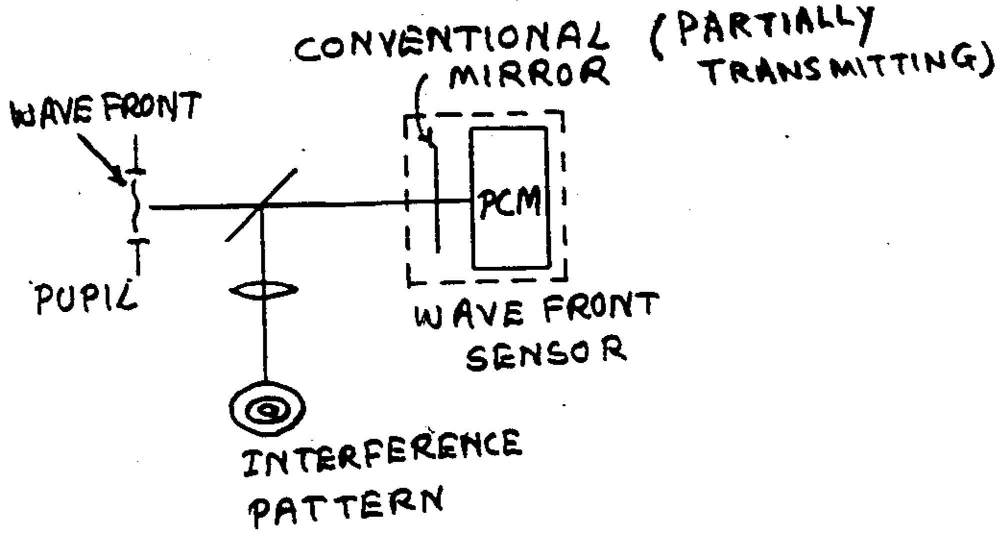
(a) (b) (c).

- SPATIAL FILTERING USED TO DERIVE REF. BEAM FROM DISTORTED BEAM.
- INPUT AND OUTPUT ENDS ISOLATED. SO IMAGE TRANSMISSION THROUGH LONG DISTORTION LENGHTS POSSIBLE.

[JOSEPH, SINGH, and Pillai, Appl. Phys. B 51(1990)219.]

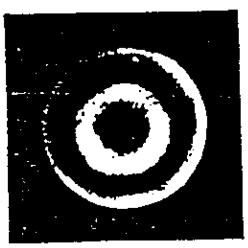
SELF-REFERENCING:

INSENSITIVE TO ENVIRONMENTAL DISTURBANCES.



PHASE-CONJUGATE FIZEAU INTERFEROMETER

M. Z. Interf. | 1.5λ Sph. aberⁿ | Unaberrated W.F.

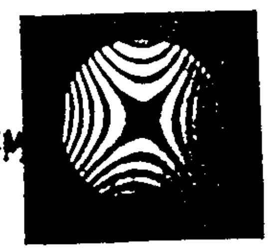


(c) c

(b) b

(a) a

2λ ASTIGMATISM (P.C.)

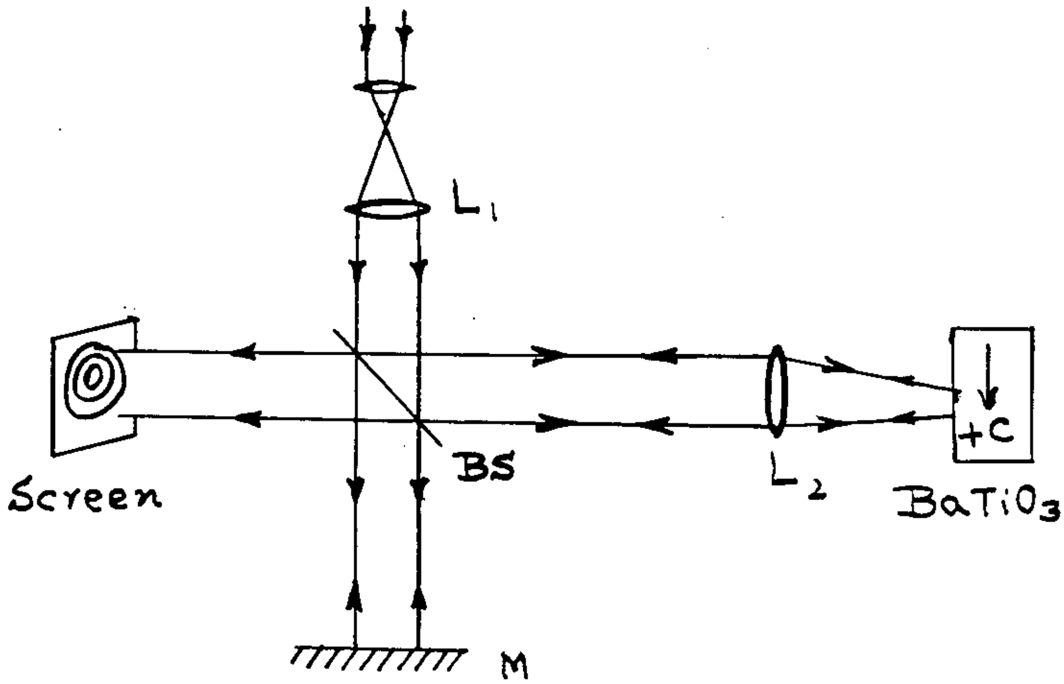


(e) e

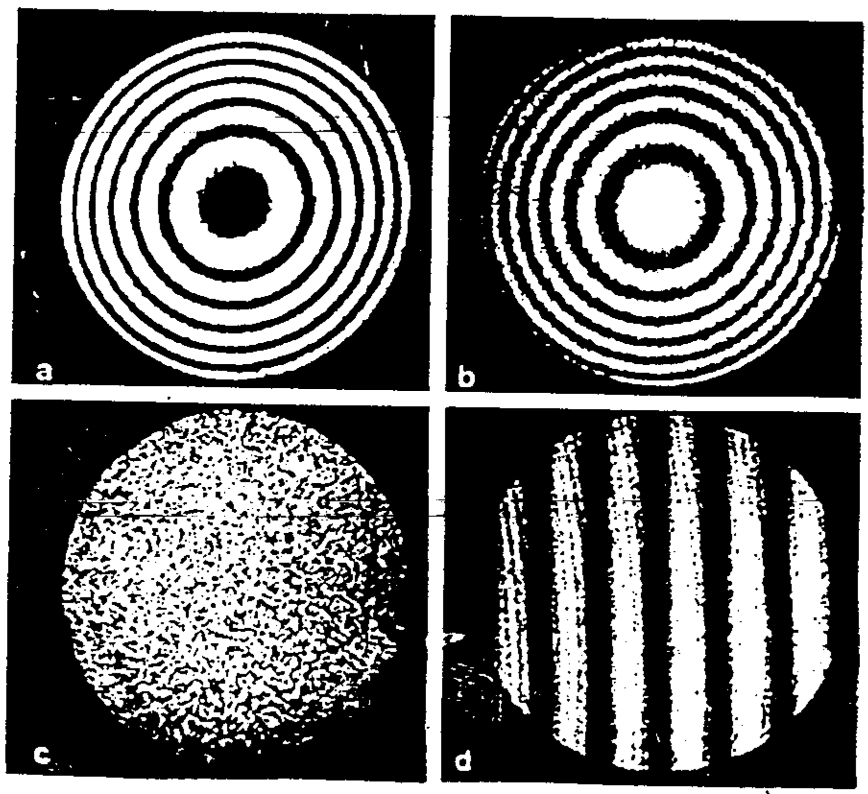
(d) d SHEARING

PHASE CONJUGATE T.G. INTERFEROMETER

[J. FEINBERG, OPT. LETT. 8, 569 (1983)]



PCM | PCM + DISTORTER



CM + DISTORTER | CM with Tilt

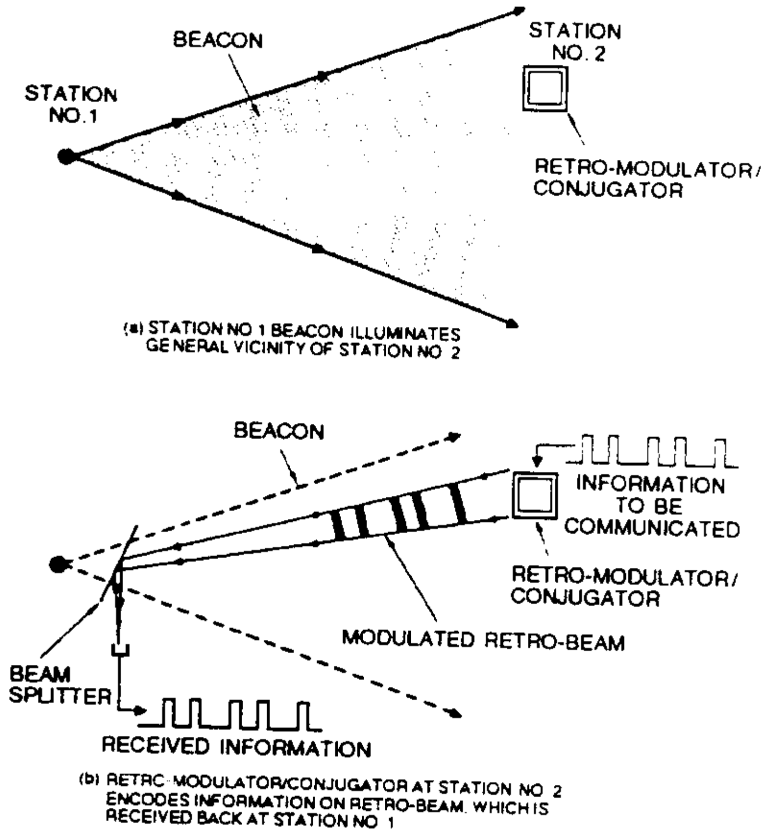
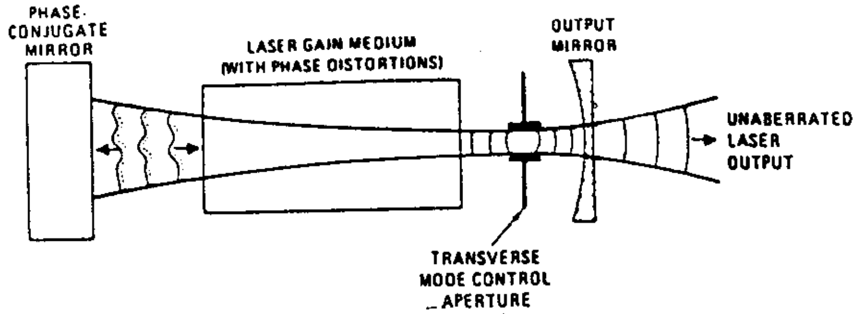
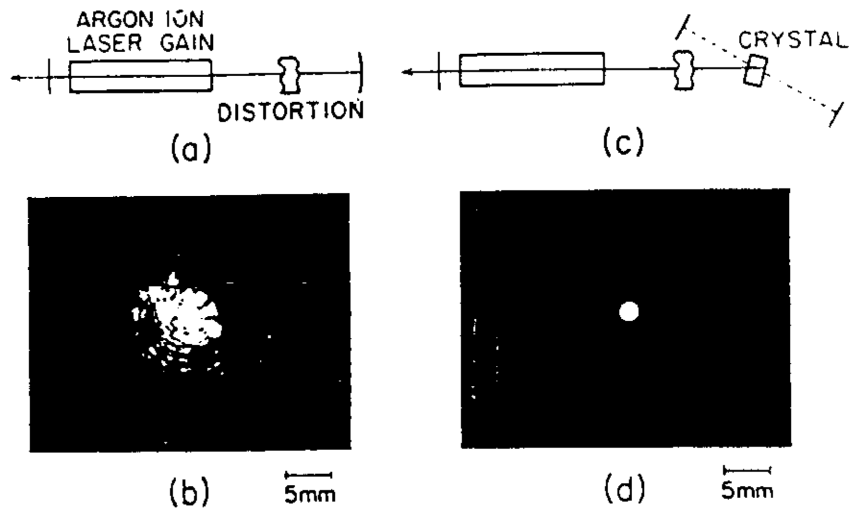


Figure 8 Basic free-space remote data link scenario using a retromodulator/conjugator, RM-PCM, at station 2 and an optical source at station 1. The goal is to relay temporal information from the RM-PCM location to the optical source location (~~after Ref. 52~~).

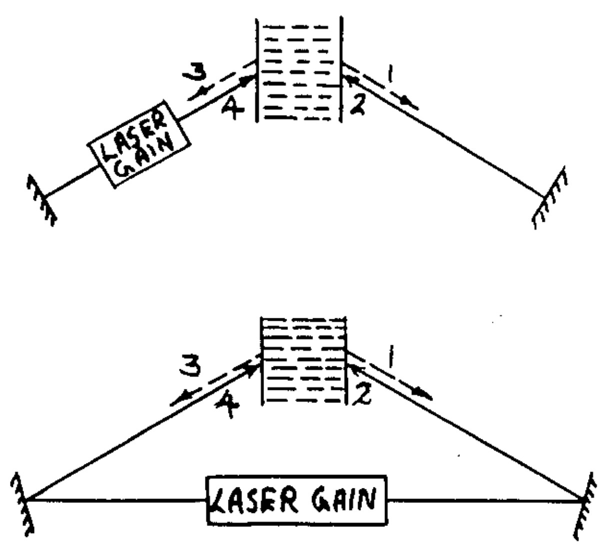
[PEPPER, PROC SPIE 739, 71 (1987)]





LASER PERFORMANCE WITH & WITHOUT PCM

[CRONIN GOLOMB et al, Appl. Phys. Lett. 41, 219 (1982)]



LASERS WITH INTRACAVITY DISTORTION

CORRECTION BASED ON 4WM

[P. GÜNTER and J.-P. HUIGNARD, PHOTOREFRACTIVE MATERIALS AND THEIR APPLICATIONS II (SPRINGER 1989) p.140 (28)

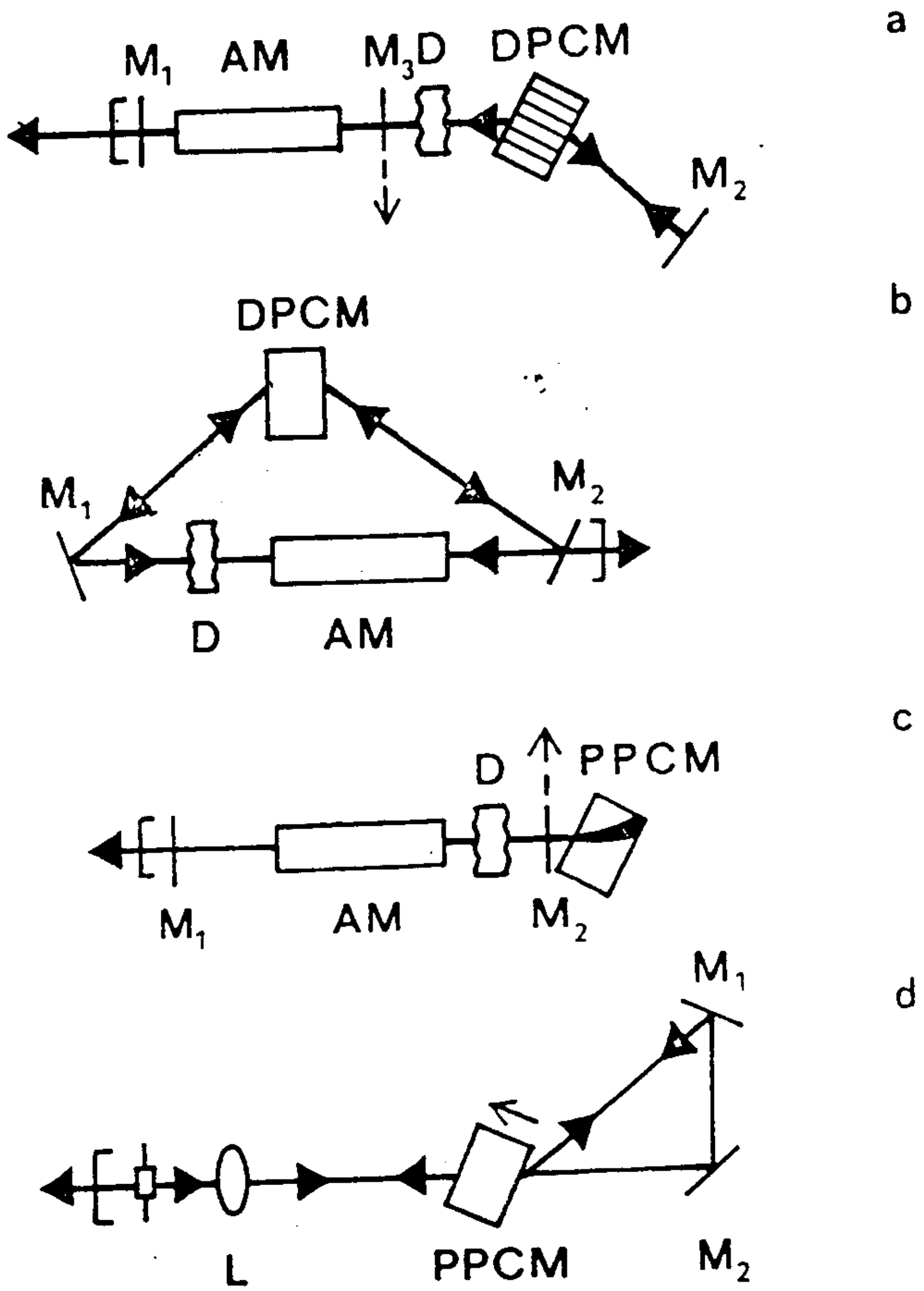


Figure 51 Hybrid lasers with photorefractive passive phase-conjugate mirros: (a) with a double phase-conjugate mirror in a linear cavity; (b) with a double phase-conjugate mirror in a ring cavity; (c) with a cat conjugator; and (d) in the feedback-loop configuration.

[S. Odoulov et al, Optical Oscillators with degenerate four-wave mixing; Harwood Acad. Publ. 1991]

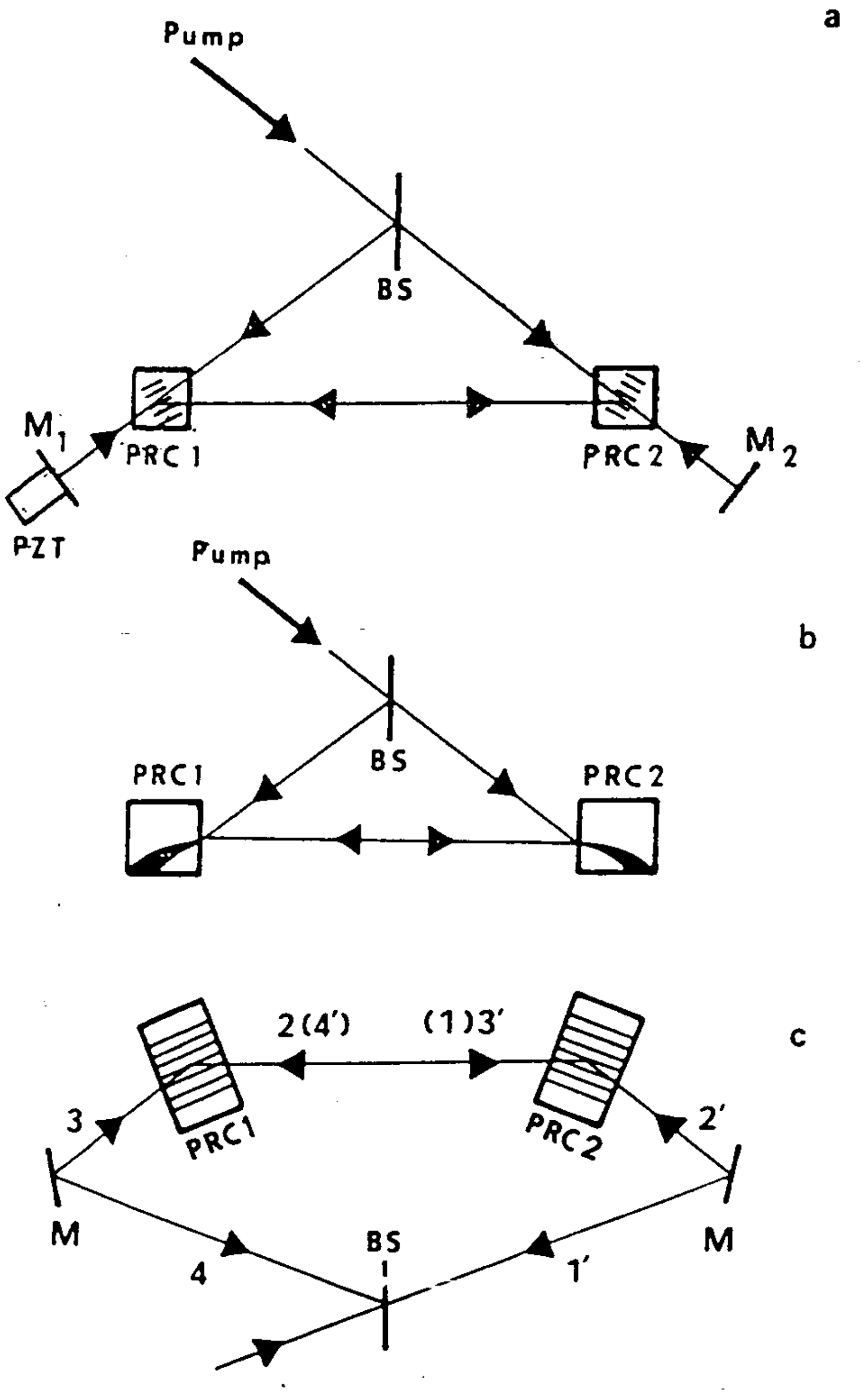
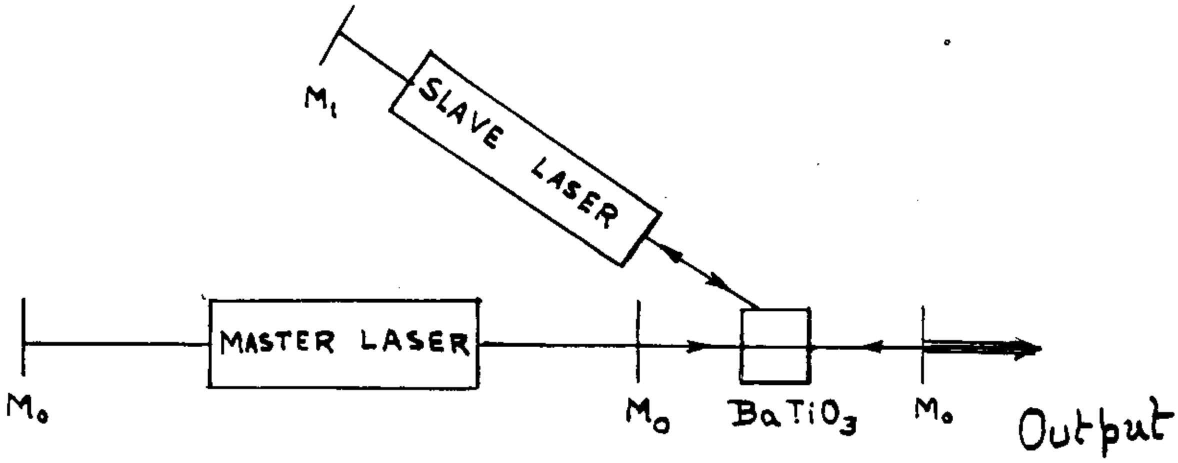
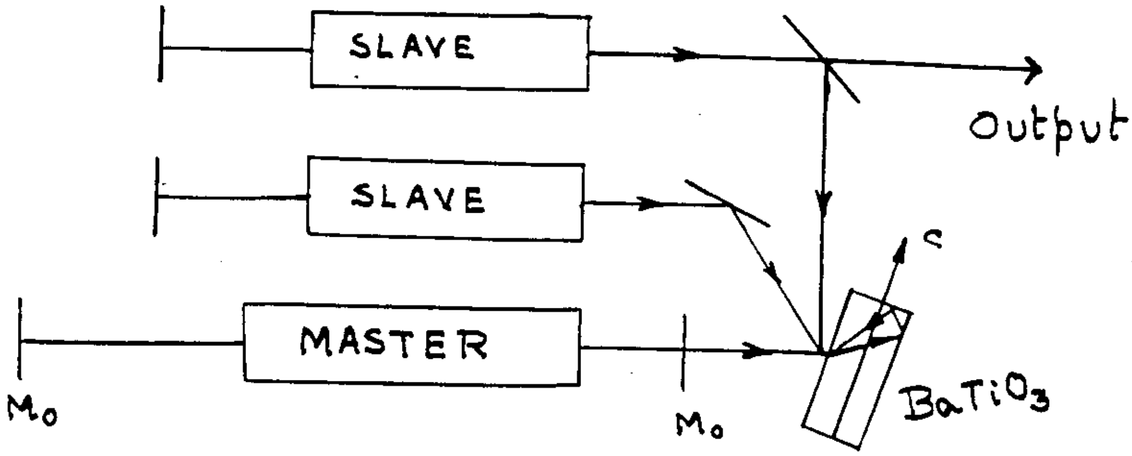
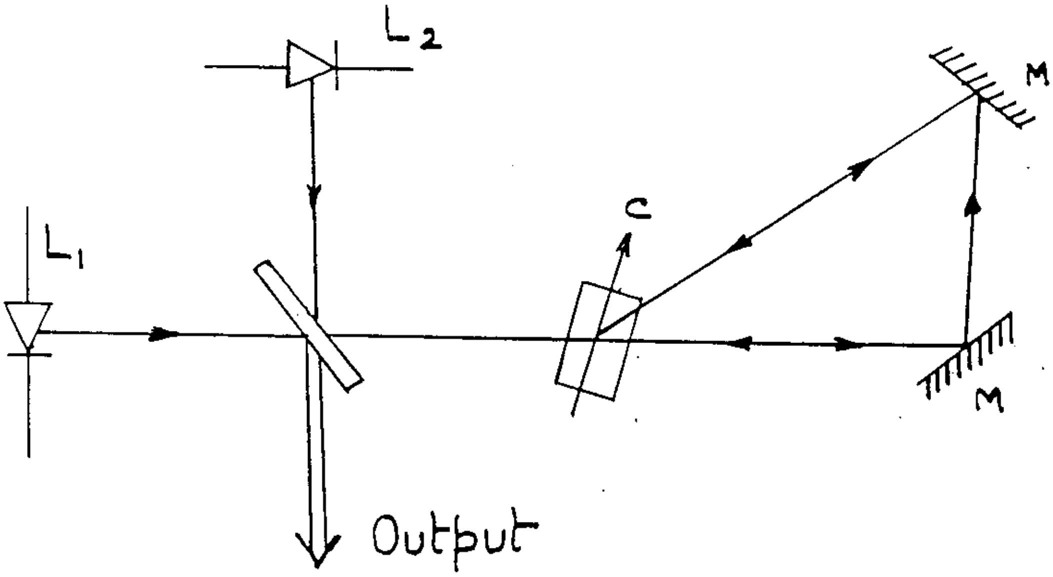


Figure 34 Phase-conjugate-mirror oscillator with (a) two externally pumped mirrors; (b) two cat conjugators; (c) two double phase-conjugate mirrors.

[S. Odoulov et al, Optical Oscillators with degenerate four-wave mixing; Harwood Acad. Publ. 1991]

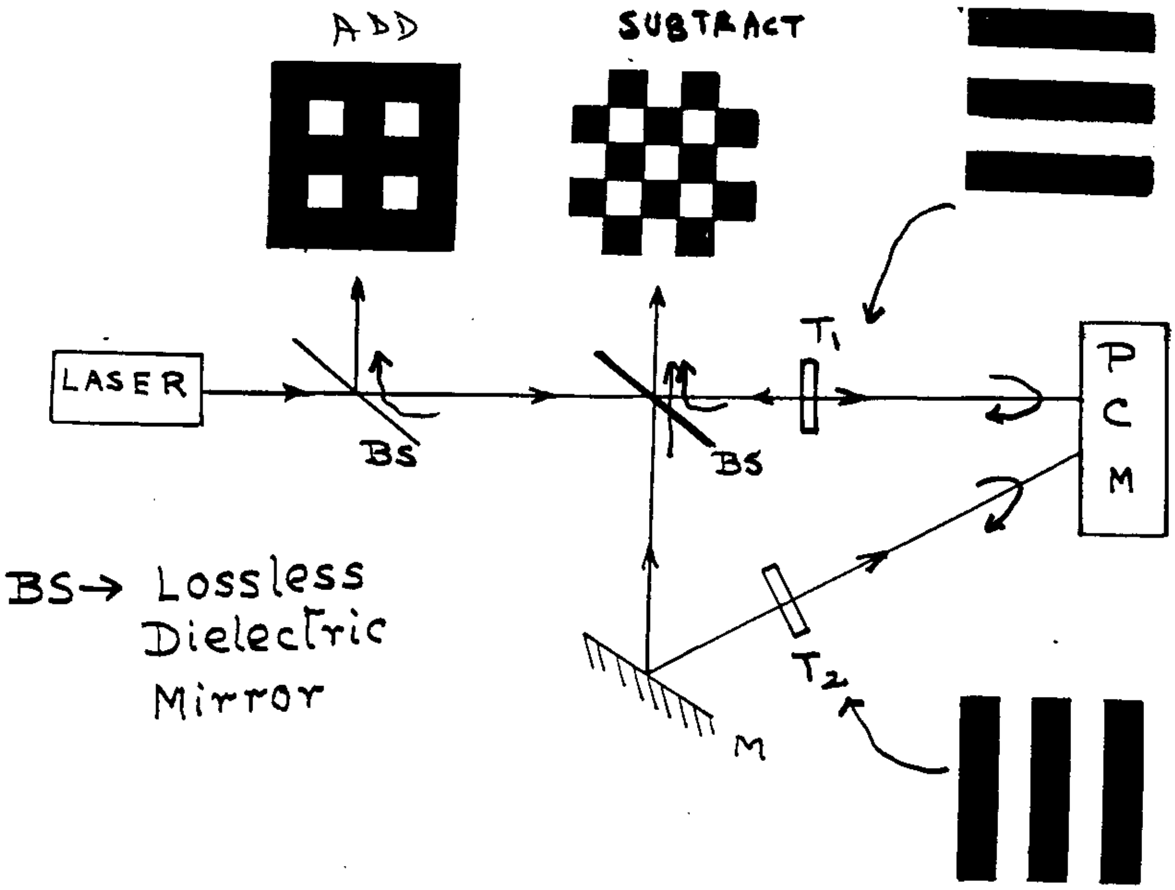






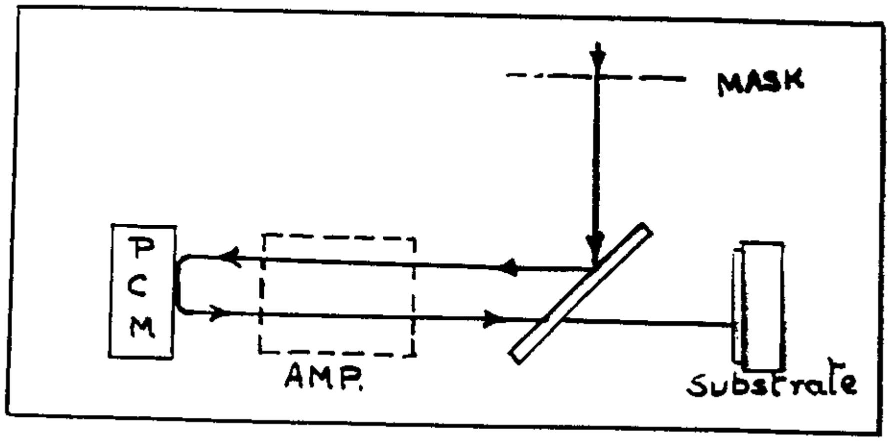
[J. FEINBERG AND D. BACHER, APPL. PHYS. LETT. 48, ~~[illegible]~~ 570 (1986)]
[D. ROCKWELL, C. GULIANO, OPT. LETT. 11, 147 (1986)]

PHASE LOCKING OF LASERS



A.E.T. Chiou et al, SPIE's O-E LASE '86, LA
Jan '86 Paper 613-34.

REAL-TIME IMAGE ADDITION AND SUBTRACTION



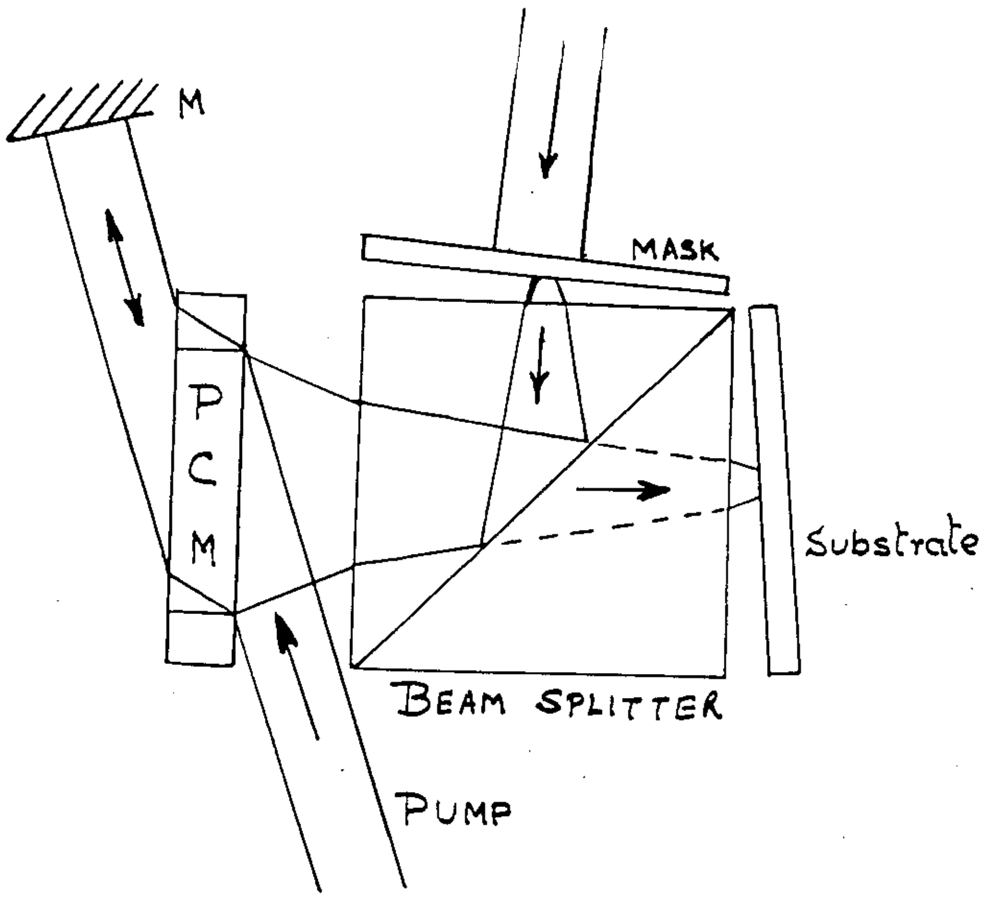
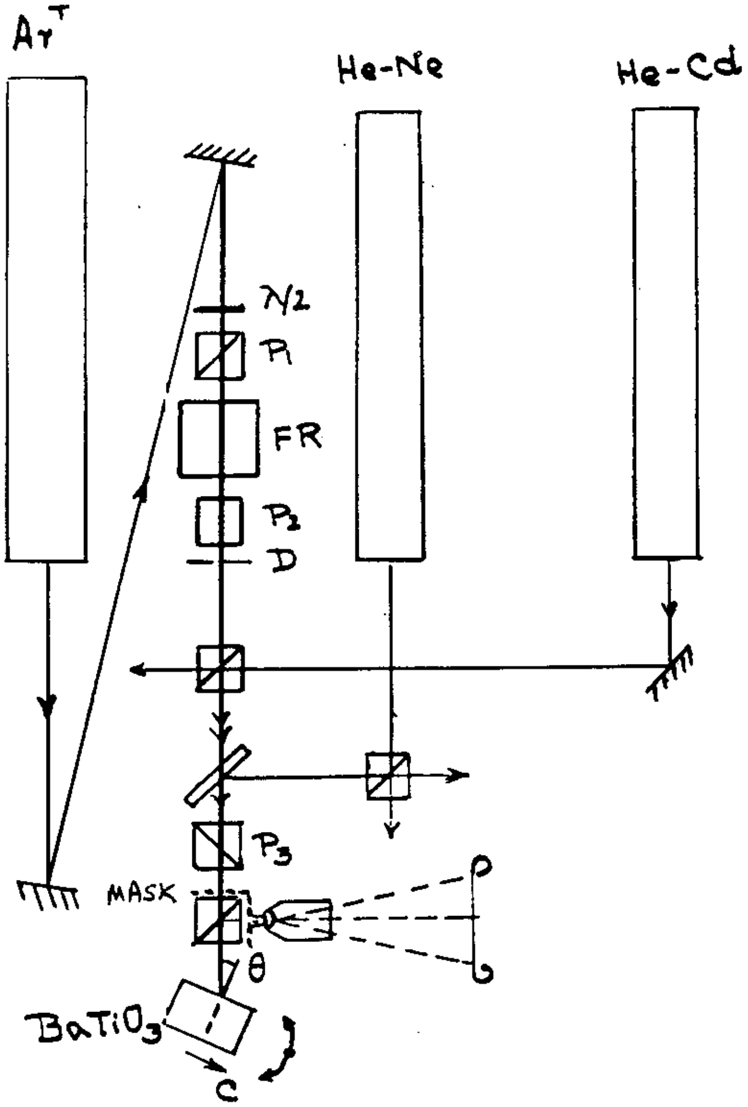


PHOTO-LITHOGRAPHY



RESOLUTION ~30 μm

[HRIBEK & GOWER, J. MOD. OPT. 36 (1989) 1011]

WHITE-LIGHT REAL-TIME PROJECTOR

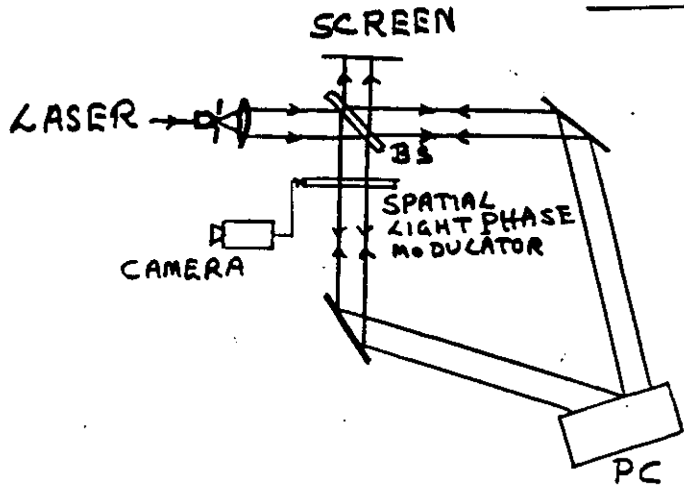
OPTICAL TRACKING NOVELTY FILTER

(D.Z. ANDERSON et al OPT. LETT. 12, [illegible] ([illegible]))

(DISPLAYS TIME-DEPENDENT FEATURES OF SCENE)

EXPLOITS FINITE RESPONSE TIME OF P.C. MIRROR.

(nanosec to secs)



SELF-PUMPED $BaTiO_3$

SPATIAL LIGHT PHASE MODULATOR

↓

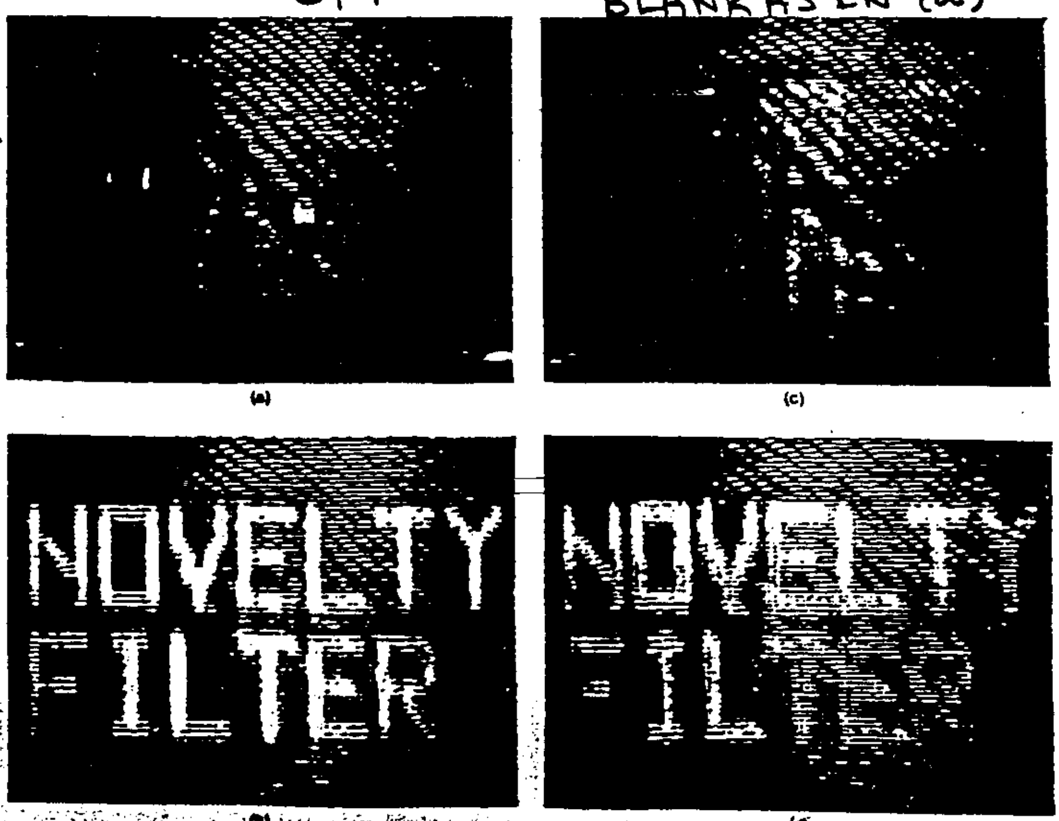
LCTV (LIQUID XTAL TV)

(DRIVING VIDEO CAMERA)

CHARACTER GENERATOR OFF

ADAPTS TO NEW SCENE BLANK AS IN (a)

INTER-FEROM. OUTPUT DARK



MOUNTAIN SCENE MEADOW

BIRD ENTER

↓

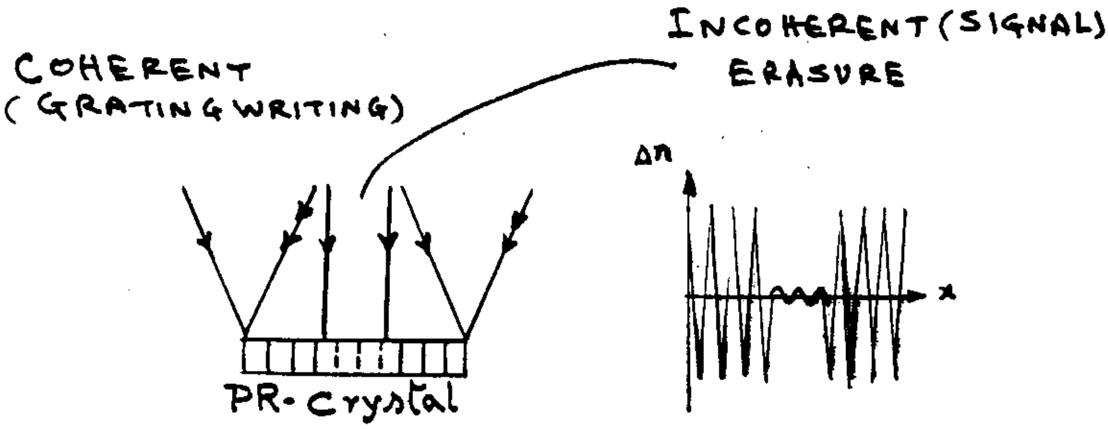
SHOWS ONLY FLYING BIRD

↓

BIRD LAND. NO OUTPUT

CHARACTER-GENERATOR DISPLAY ACTIVATED

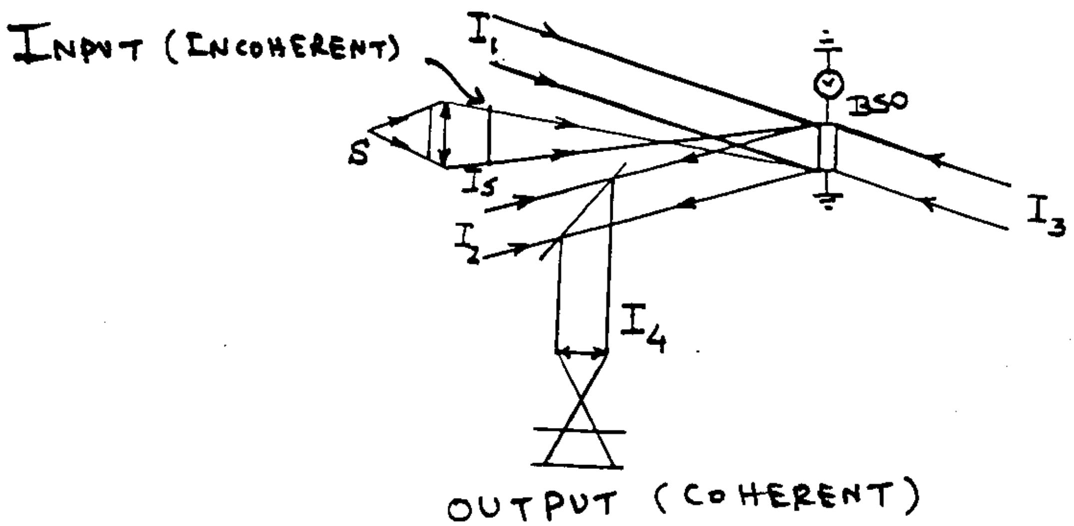
DISPLAY DEACTIVATED



GRATING + SIGNAL; <u>OR</u> SIGNAL + GRATING; <u>OR</u> SIMULTANEOUS

<u>INCOHERENT-TO-COHERENT CONVERTER</u>

[P. Günter and J.-P. Huignard, Eds "Photorefractive materials and their applications; Springer, 1989] Chap. 7



READOUT WAVELENGH COULD BE DIFFERENT THAN WRITING WAVELENGTH

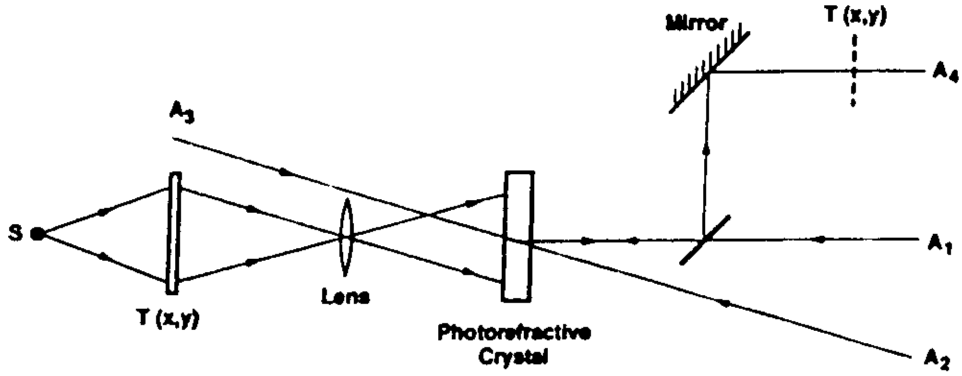


Figure 11.5. A photorefractive spatial light modulator (SLM) using four-wave mixing. The device is also known as photorefractive incoherent-coherent optical converter (PICOC) [12].

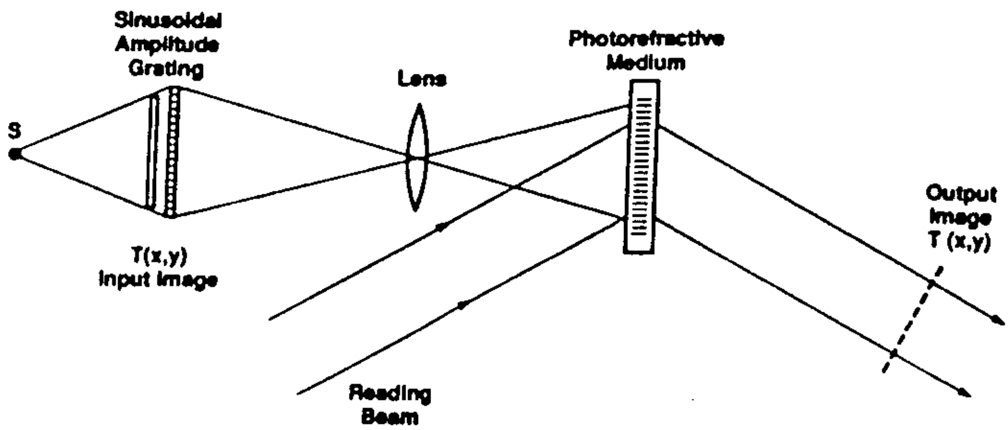


Figure 11.6. A high contrast photorefractive SLM.

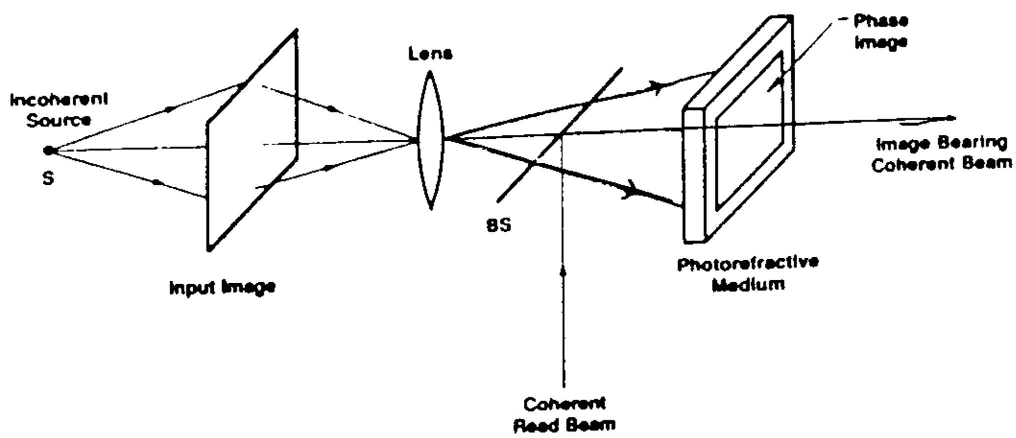
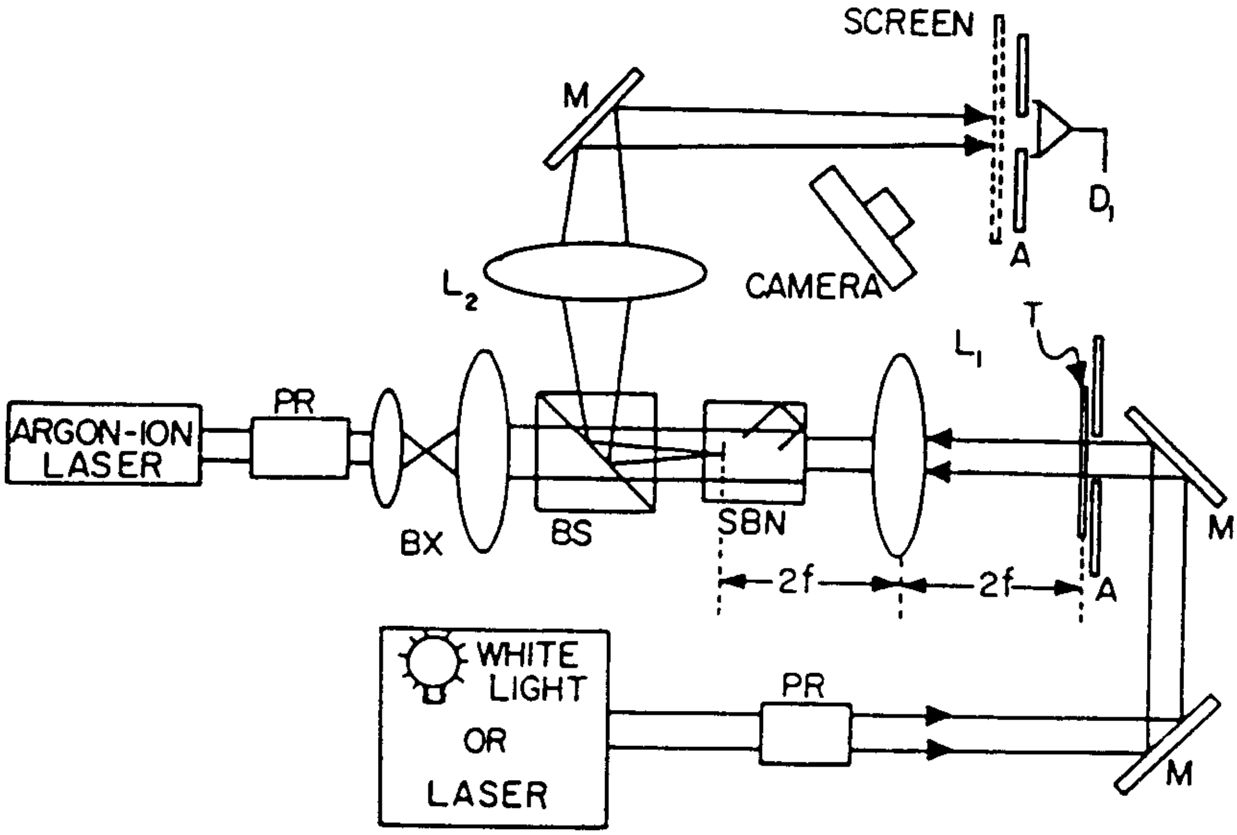


Figure 11.7. A nonholographic photorefractive SLM

[P. Yeh, Introduction to photorefractive non-linear optics; Wiley 1993]



Experimental arrangement used to demonstrate the principle of incoherent-to-coherent conversion in a self-pumped phase conjugator. PR's, polarization rotator; BX, beam expander; T, binary transparency; BS, beam splitter; A, 1 mm diameter aperture; M's, mirrors. The incoherent white-light source is a xenon lamp.