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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This optoelectronic workshop represents the first of a series of intensive academic/government interactions in the field of advanced electro-optics as part of the Army sponsored University Research Initiative. The workshops are a collaboration between the Center for Opto-Electronic Systems Research at the University of Rochester, Rochester, New York and the U.S. Army Center for Night Vision and Electro-Optics, Ft. Belvoir, Virginia. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.			
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The Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

I

**PHASE CONJUGATION/STRONGLY DRIVEN
ATOMIC SYSTEMS**

March 22, 1988

sponsored jointly by

**ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester**

OPTOELECTRONIC WORKSHOP
ON
PHASE CONJUGATION/STRONGLY DRIVEN ATOMIC SYSTEMS

**Organizer: ARO-URI-University of Rochester
and Center for Night Vision and Electro-Optics**

- 1. INTRODUCTION**
- 2. SUMMARY -- INCLUDING FOLLOW-UP**
- 3. VIEWGRAPH PRESENTATIONS**

**A. Center for Opto-Electronic Systems Research
Organizer -- Robert Boyd**

**Recent Results in Phase Conjugation
Robert Boyd**

**Laser Beam Combining in Atomic Vapors
Kenneth MacDonald**

**B. Center for Night Vision and Electro-Optics
Organizer -- Richard Utano**

**Applications of Phase Conjugation
Richard Utano**

**Optical Phase Conjugation in Photorefractive
Materials
Edward Sharp**

**Stimulated Brillouin Scattering for Directed
Energy Lasers
Lynn Garn**

- 4. LIST OF REFERENCES**
- 5. LIST OF ATTENDEES**
- 6. DISTRIBUTION**



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1. INTRODUCTION

This workshop represents the first of a series of intensive academic government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO URI) and Dr. Rudy Buser, NVEOC.

2. SUMMARY AND FOLLOW-UP ACTIONS

Dr. Buser opened up the meeting with initial remarks on the true driving force of NVEOC tech base mission. It consists in introducing new technology in the military arena to address areas of deficiencies in Army programs. This introduction included the use of phase conjugation for solving problems in laser development for military application. Dr. Buser also stressed the point (has he did many times during the meeting) that the technology being developed must consider the requirements necessary for fieldable laser systems.

The first presentation was on the use of stimulated Brillouin scattering for solid state lasers presented by Richard Utano of NVEOC. It highlighted the past work done at Night Vision in this field, namely phase conjugation and its importance to solid state laser development; and some technical issues that still need to be resolved. Issues such as competing nonlinear processes and energy scaling were of utmost importance to the Army.

The next presenter was Dr. Ed Sharp and he described the effort NVEOC is planning in photorefractive materials. This work on characterizing materials and determination of necessary laser parameters for filters and other applications, generated much interest with the Rochester personnel, especially Dr. Sharp's work with the tungsten bronze crystals.

To complete discussion of NVEOC interest in phase conjugation, Dr. Lynn Garn presented phase conjugation potential for neural networks for automatic target recognition. Though the properties of optical phase conjugation are not exercised, there are similar techniques being employed for this optical computing process. This discussion was centered on NVEOC's view of the status of the technology, and its potential versus conventional electronic techniques.

Dr. Boyd then gave an overview of the Institute of Optics work in phase conjugation. He discussed work on single pass aberration correction, coherence issues of phase conjugated light, Brillouin enhanced four-wave-mixing and vector phase conjugation. The vector phase conjugation via stimulated Rayleigh wing scattering or other possible methods, generated interest by NVEOC personnel. Such a process could counter birefringence problems associated with high average power lasers.

Ken MacDonald, Post Doc, then presented work on laser beam combining in atomic vapors. Both probe beam amplification and beam combining experiments were discussed. To date, 25% energy transfer was obtained in Na vapor which is promising but the criteria for such effects are very frequency dependent.

These presentations were then followed by discussion on the many techniques each facility was experimenting on. Areas of overlap were discussed and ideas for potential collaboration were identified. The outcome implies that there are several areas where mutual interest exists: In the photorefractive field of phase conjugation, which is still undergoing vast amounts of basic research, the overlap and interest of the University is evident. In the field of stimulated scattering, the issues of concern are not necessarily fundamental, and overlap less directly with the University's goals.

On the basis of this workshop, the following ideas for continued interaction have been developed:

a. Photorefractive Nonlinear Optics

It would be interesting to perform additional measurements to establish that self-pumped phase conjugation in the tungsten bronzes is inherently more stable than in barium titanate, with roughly equivalent optical properties leading to PCM's with very different stability characteristics.

Also, it would be important to perform measurements to establish to what extent incoherent light (spatially and/or temporarily) can be used to excite nonlinear optical processes in these materials.

NVEOC could help to get started in these areas by helping to obtain photorefractive tungsten bronze crystals.

b. Laser Beam Combining

The University will try to establish the appropriate scaling laws for laser beam combining in atomic vapors, and from these scaling laws attempt to establish (through discussion with NVEOC personnel) applications in the field of laser development.

c. Vector Phase Conjugation

Vector phase conjugation appears to be a promising technique for removing the effects of thermally induced radial birefringence from laser rods. Through discussions with NVEOC personnel and through laboratory measurements, the University will determine whether vector phase conjugation has implications to the NVEOC laser program.

**CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
RECENT RESULTS IN PHASE CONJUGATION**

Research in Nonlinear Optics

Professor

Robert W. Boyd

B.S., Massachusetts Institute of Technology
Ph.D., University of California at Berkeley

Post Docs

Michelle S. Malcuit

B.A., New York State University
Ph.D., University of Rochester

Kenneth R. MacDonald

B.S., Worcester Polytechnic Institute
M.A., Johns Hopkins University
Ph.D., University of Southern California

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Alexander L. Gaeta

B.S., University of Rochester
M.S., University of Rochester

Daniel J. Gauthier

B.S., University of Rochester
M.S., University of Rochester

Mark L. Gruneisen

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M.S., University of Rochester

Martti Kauranen

M.S., Helsinki University of Technology

Jeffery J. Maki

B.S., Lewis and Clark College

Edward Miller

B.S., University of Rochester
M.S., University of Rochester

Mark D. Skeldon

B.S., Old Dominion University
M.S., Old Dominion University
M.S., University of Rochester

Bryan Stone

B.S., University of Rochester

Wayne R. Tompkin

B.A., Kenyon College

Secretary

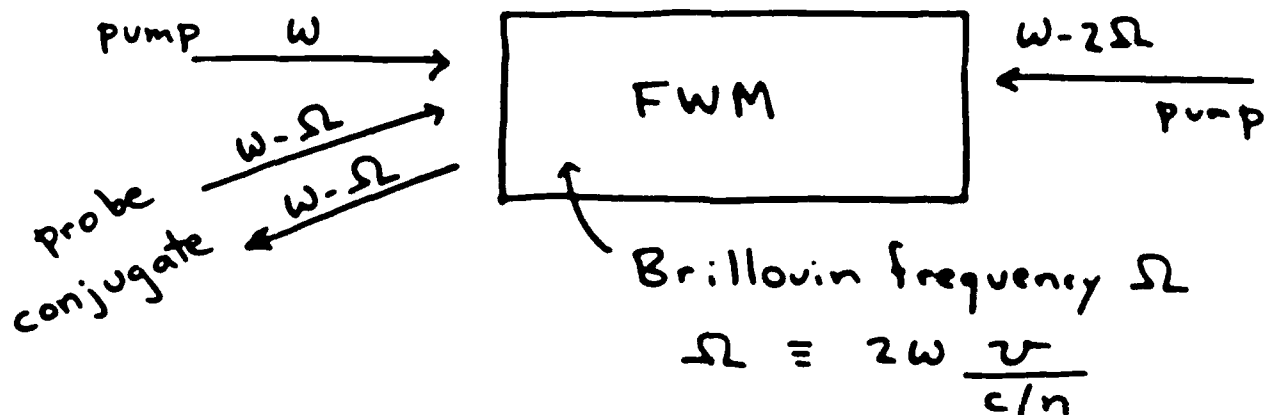
Lynne V. McCoy

B.A., University of Rochester

BRILLOUIN ENHANCED FOUR-WAVE MIXING

Signal and pump waves differ in frequency by Brillouin frequency of medium.

Four-wave mixing process mediated by intense sound wave.



Reflectivity can readily exceed 100%.

No requirement on pump frequency

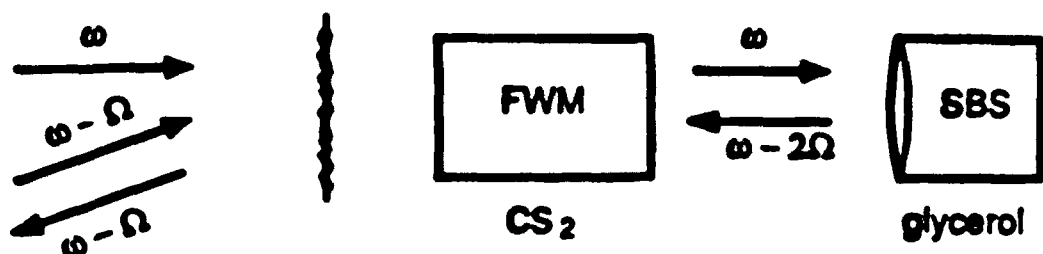
No frequency shift

Good energy transfer from pumps to conjugate

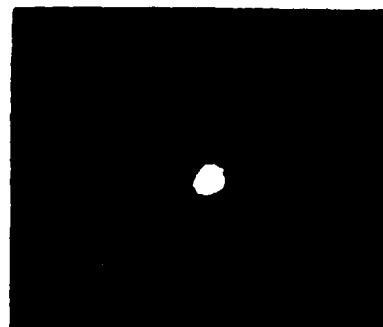
P. Narum and R. W. Boyd, IEEE J. Quantum Electron
(1987)

M. D. Skeldon, P. Narum, and R. W. Boyd, Opt. Lett.
(1987).

Phase Conjugation with Aberrated Pump Waves



PC signal
with no aberrator



PC signal
with aberrated pump waves

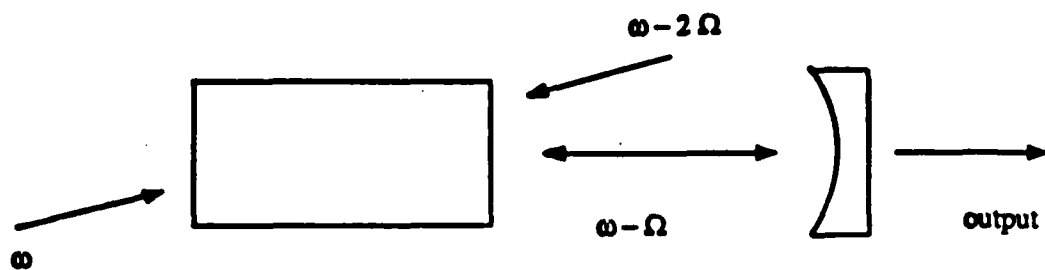


Degree of aberration
on the waves

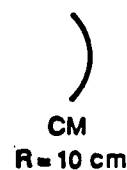
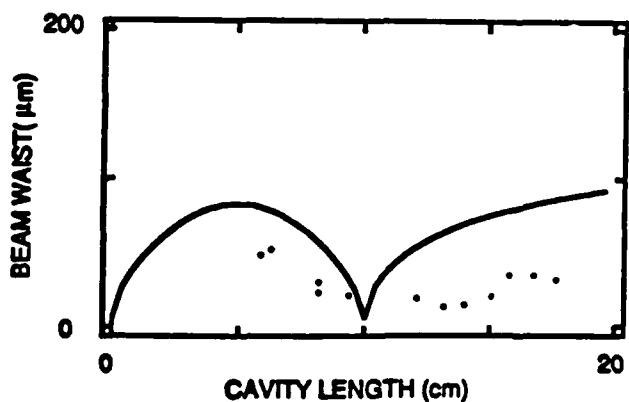
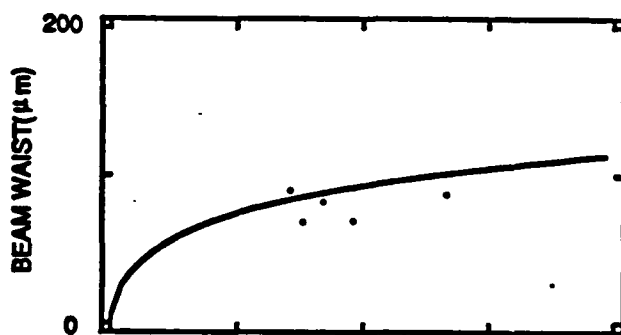
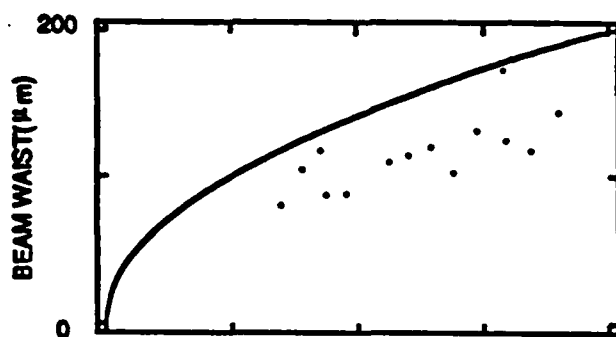


Phase Conjugate Oscillator

Brillouin Enhanced Four Wave Mixing



Output beam characteristics

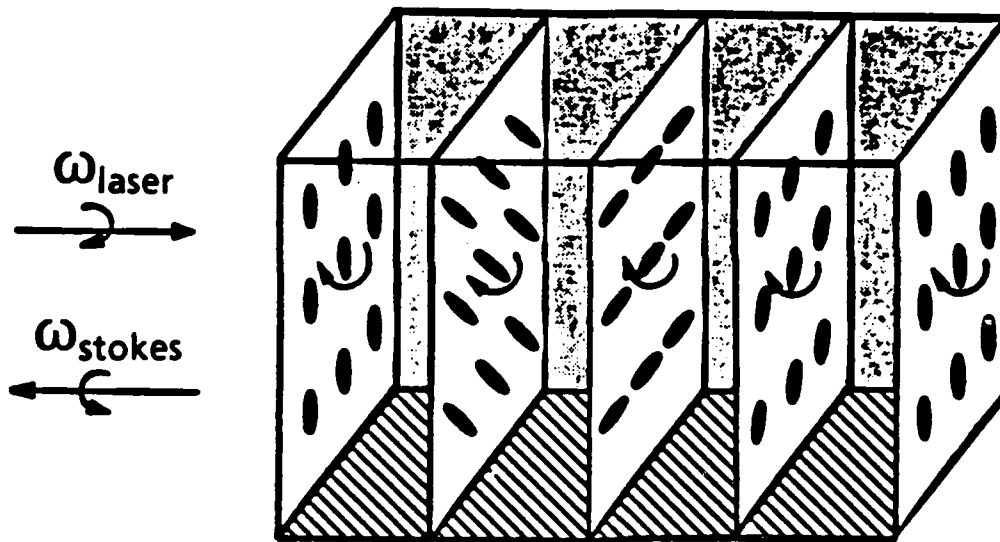


Phase Conjugation by Stimulated Rayleigh-Wing Scattering

- Provides complete vector phase conjugation
- Fast response time allows conjugation of picosecond pulses

Rayleigh-wing scattering:

Scattering from non-uniformly oriented anisotropic molecules.



Questions:

How does the SRWS treat circularly polarized light?
Elliptically polarized light? Randomly depolarized light?

Competing effects: stimulated Brillouin scattering, stimulated Raman scattering, self focusing, self-phase modulation.

Vector Phase Conjugation by DFWM

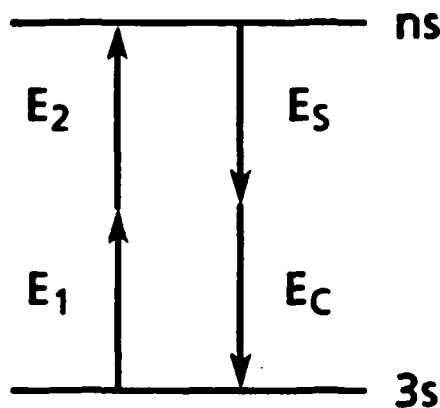


$$\vec{E}_c = r \hat{E}_s^* A_s^* e^{-ik_s z}$$

polarization conjugation

wavefront conjugation

Two-photon resonant enhancement:



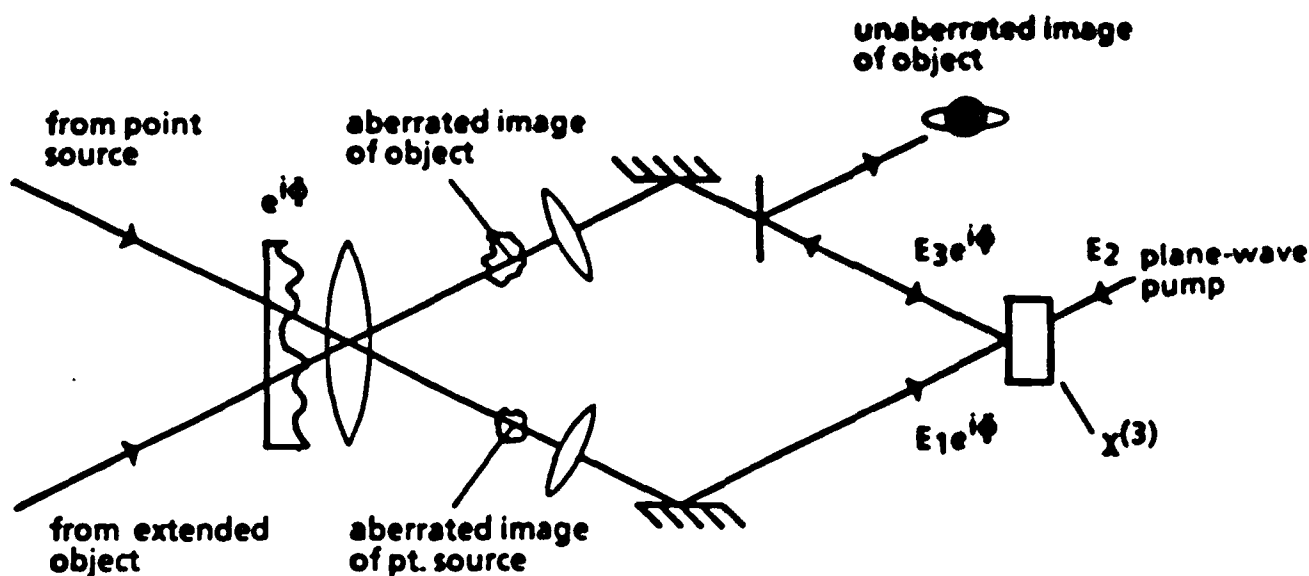
(Grynberg, 1984)

- Observed vector phase conjugation for weak pump intensities ($|r|^2 \sim 10^{-4}$)
- Observed degradation of the fidelity of phase conjugation for strong pump intensities ($|r|^2 \sim 10^{-2}$)

Next:

- Study effects of geometries
- Need to understand saturation effects in two-photon resonant systems

Single-pass Aberration Correction

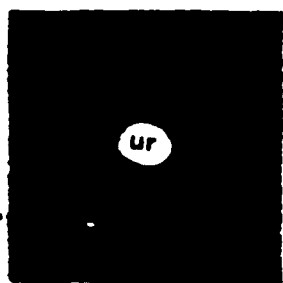


$$P_{NL} \sim (E_1 e^{i\Phi}) E_2 (E_3 e^{i\Phi})^* = E_1 E_2 E_3^*$$

Φ = phase distortion introduced by aberrator

- Thin phase distorter
- Coherent imaging

(Goodman, 1966)



original object

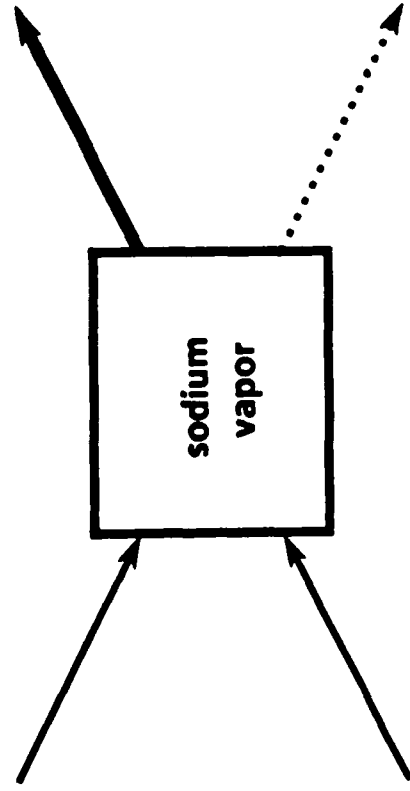


aberrated image of object



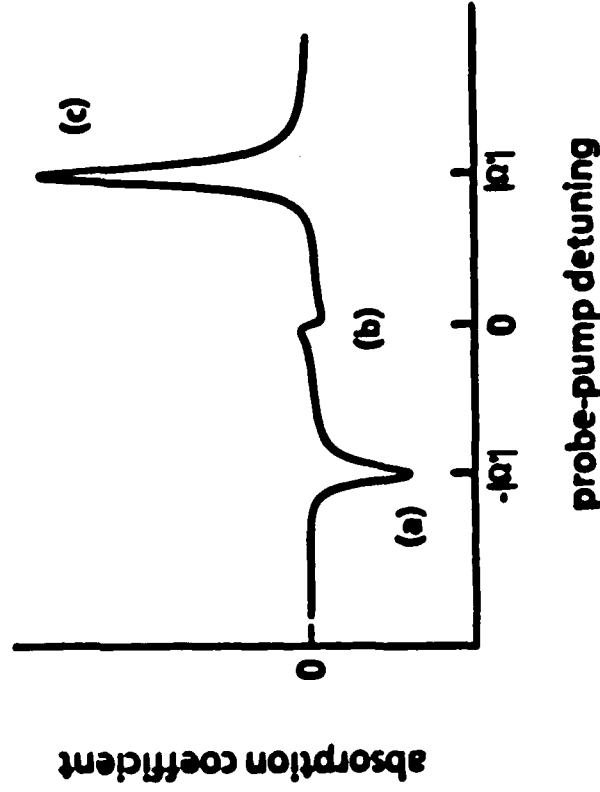
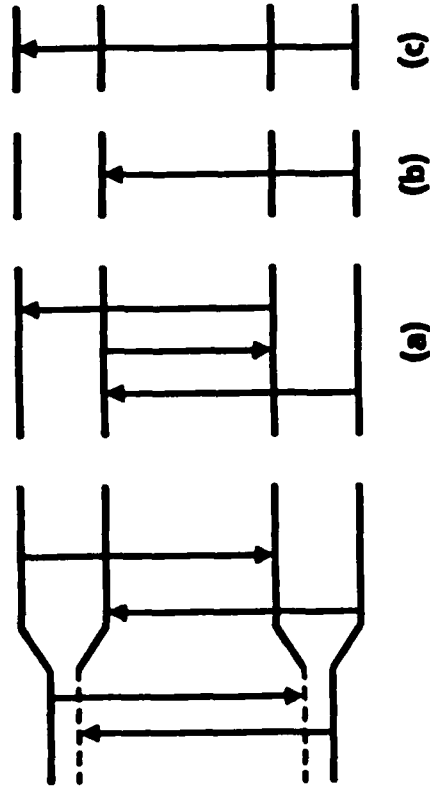
unaberrated image recovered by phase conjugation

LASER BEAM COMBINING IN SODIUM



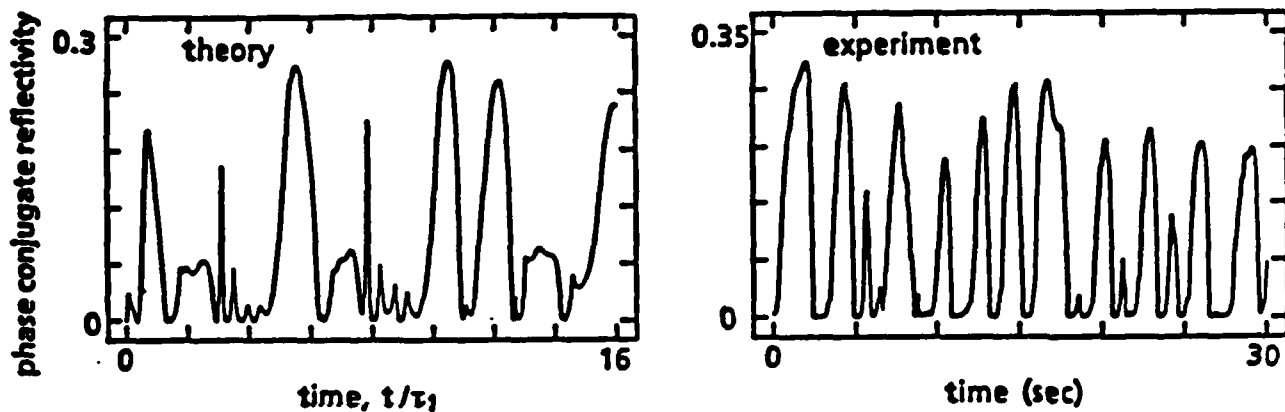
- 38-times increase in the intensity of a weak probe beam has been observed.
- Measurements of energy transfer for equal-intensity beams are now in progress.

DYNAMIC STARK EFFECT



Instabilities and Chaos in Phase Conjugation

Observed chaotic behavior in a
barium titanate,
internally self-pumped PCM.



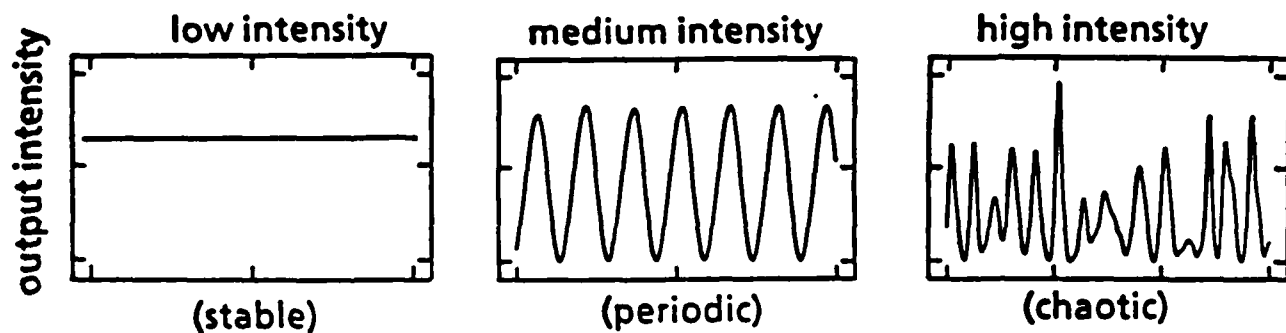
- Instability due to coupling between all four nonlinear refractive-index gratings.
- System evolves temporally on a strange attractor characterized by a correlation dimension $\nu = 1.3$ and an order-2 Renyi entropy $K_2 = 7.2$ bits/sec.

Phys. Rev. Lett., 58, 1640 (1987)

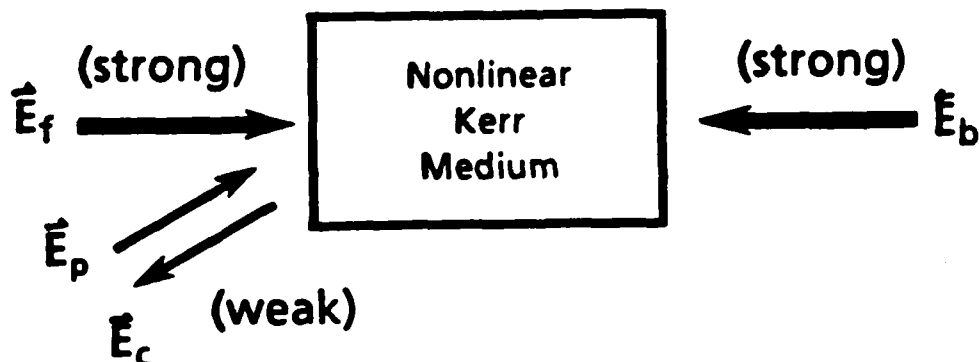
Temporal Instabilities of Counterpropagating Light Fields



- simple interaction can exhibit complex behavior
- output polarization and intensity can fluctuate periodically or chaotically in time

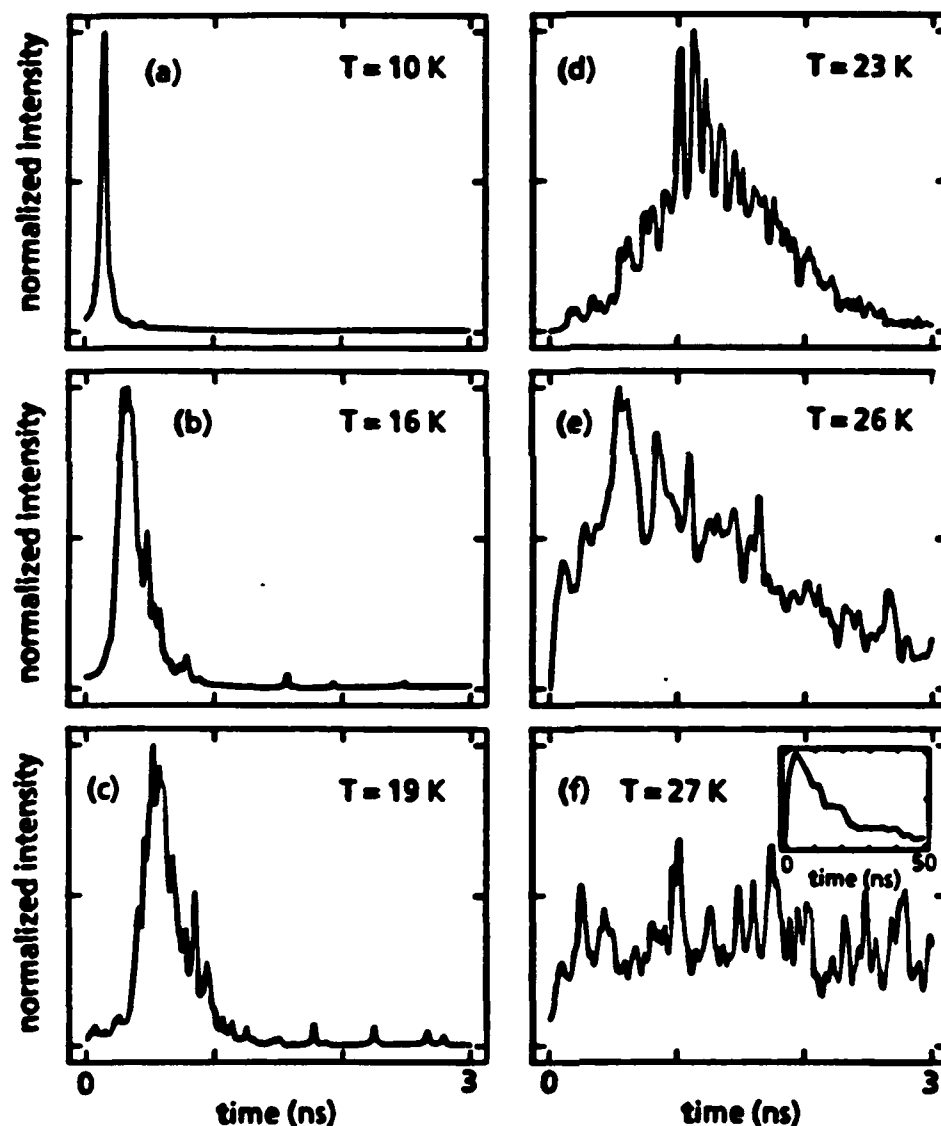
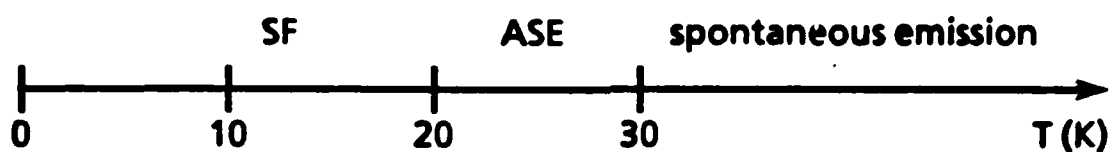


- instability threshold is lower when tensor nature of the interaction is treated (Gaeta et al., Phys. Rev. Lett. (1987))
- limitation on performance of phase conjugation via FWM



What is the difference between superfluorescence and amplified spontaneous emission?

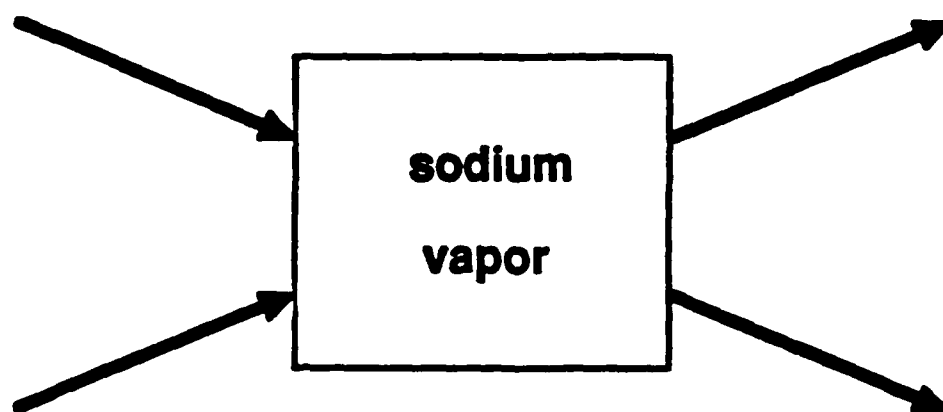
- Study the emission of $\text{KCl}:\text{O}_2$ as a function of temperature.



Malcuit, Maki, Simkin, and Boyd, Phys. Rev.Lett. (1987)

**CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
LASER BEAM COMBINING IN ATOMIC VAPORS**

LASER BEAM COMBINING THROUGH THE NONLINEAR RESPONSE OF A STRONGLY DRIVEN ATOMIC TRANSITION



I. Weak-probe-wave Amplification

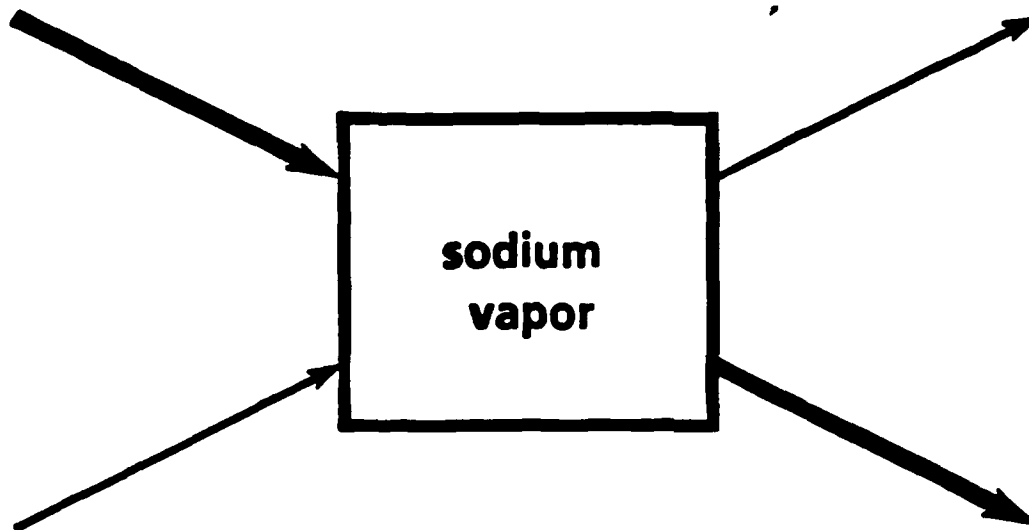
M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd

II. Coupling of Two Intense Beams

A. L. Gaeta, M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd

**The Institute of Optics
University of Rochester**

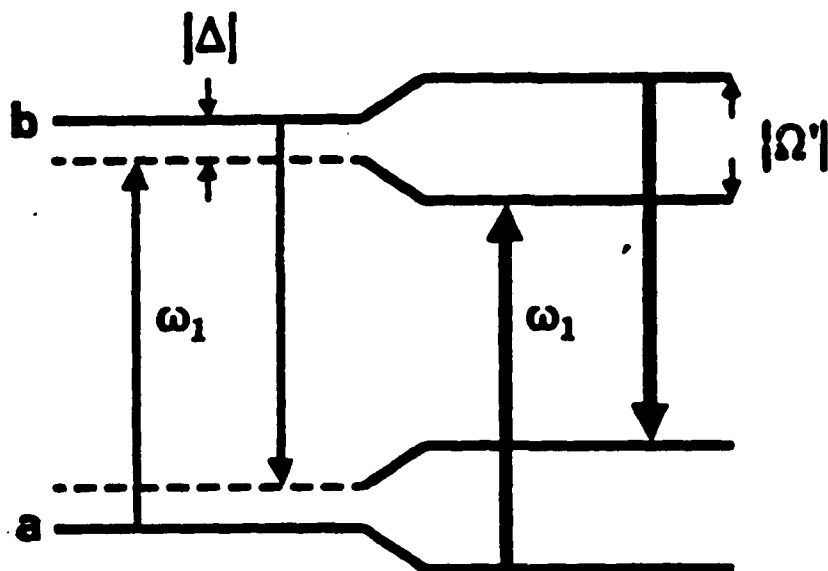
**INDUCED GAIN AND MODIFIED ABSORPTION
OF A WEAK PROBE BEAM
IN A STRONGLY DRIVEN SODIUM VAPOR**



- system of two-level atoms
- probe-wave amplification
- 38-fold increase in probe intensity measured
- atomic motion, collisional dephasing

M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd, to be published in
J. Opt. Soc. Am. B, January, 1988.

ORIGIN OF SPECTRAL FEATURES: THE AC STARK EFFECT



generalized Rabi frequency $\Omega' = \frac{\Delta}{|\Delta|} [\Omega^2 + \Delta^2]^{1/2}$

SOLUTION TO DENSITY MATRIX EQUATIONS

- Two-level atom
- Pump field treated correctly to all orders
- Probe field treated to only first order

Probe-Wave Absorption Coefficient:

$$\alpha(\delta) = \alpha_0 (\rho_{bb} - \rho_{aa})^{dc} \operatorname{Im} \left[\frac{(\delta + i/T_1)(\delta - \Delta + i/T_2)(\Delta - i/T_2) - \Omega^2 \delta/2}{(\Delta - i/T_2)D(\delta)} \right]$$

$$D(\delta) = (\delta + i/T_1)(\delta + \Delta + i/T_2)(\delta - \Delta + i/T_2) - \Omega^2(\delta + i/T_2)$$

Steady-State Population Inversion:

$$(\rho_{bb} - \rho_{aa})^{dc} = \frac{(1 + \Delta^2 T_2^2)(\rho_{bb} - \rho_{aa})^0}{1 + \Delta^2 T_2^2 + \Omega^2 T_1 T_2}$$

probe-pump detuning $\delta = \omega_3 - \omega_1$

dipole dephasing time T_2

population relaxation time T_1

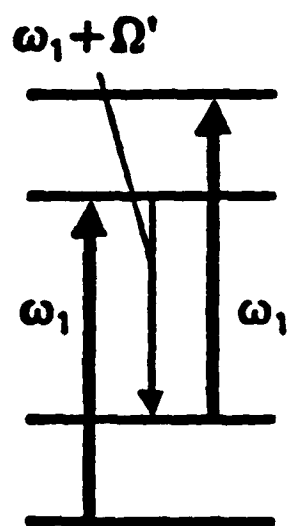
pump-resonance detuning $\Delta = \omega_1 - \omega_{ba}$

on-resonance Rabi frequency $\Omega = |\mu_{ba}| E_1 / \hbar$

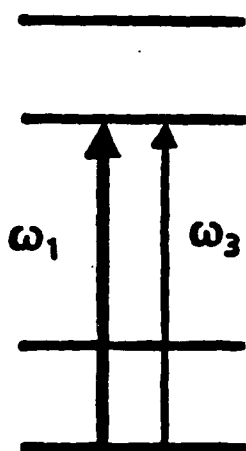
B. R. Mollow, Phys. Rev. A 5, 2217 (1972)

R. W. Boyd, M. G. Raymer, P. Narum, and D. J. Harter, Phys. Rev. A 24, (1981)

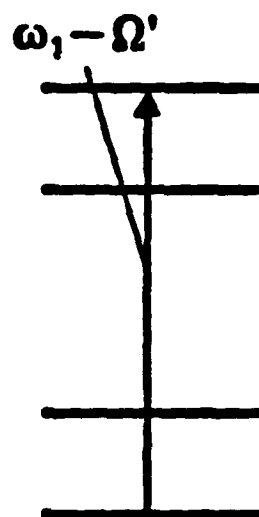
INDUCED GAIN AND MODIFIED ABSORPTION OF A WEAK PROBE WAVE



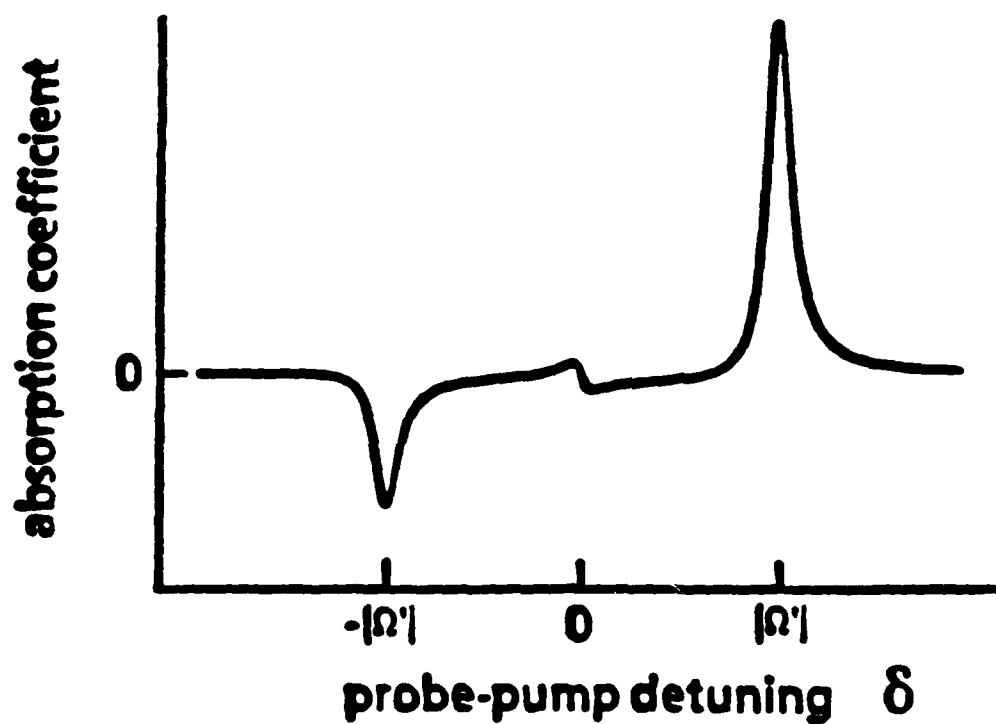
Three-Photon
Effect



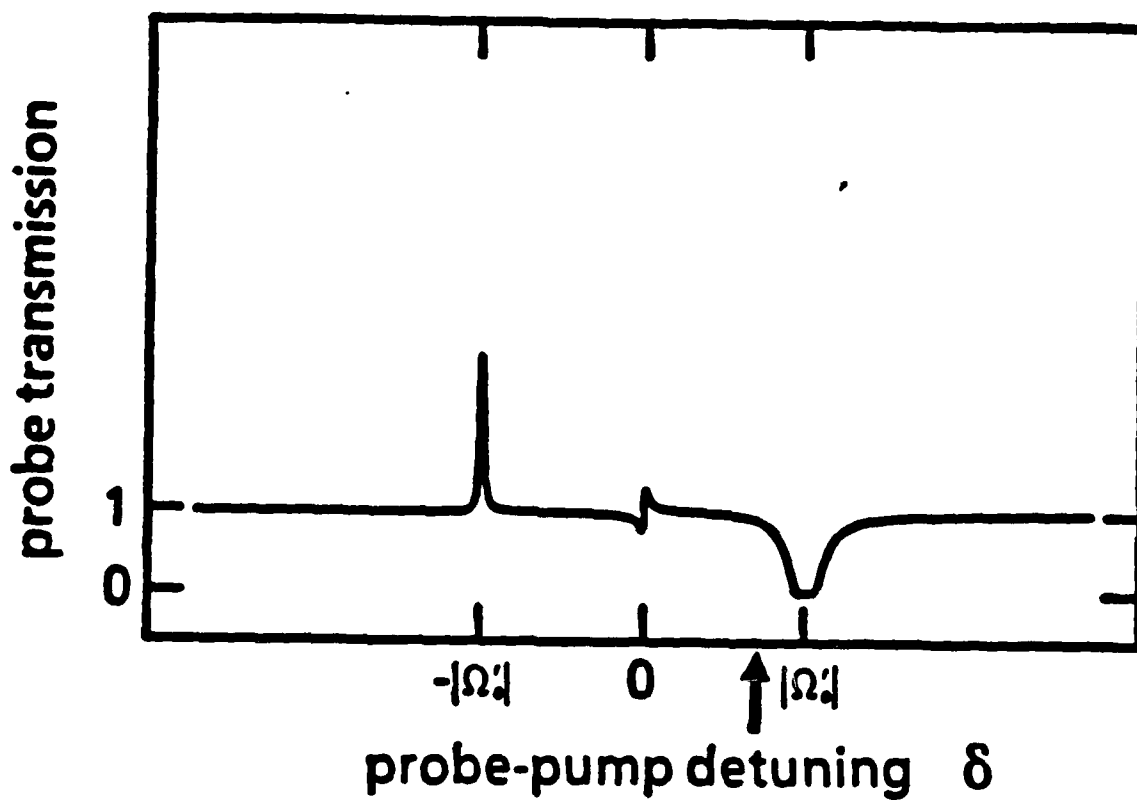
Nearly Degenerate
Coupling



AC Stark-Shifted
Resonance



PROBE TRANSMISSION SPECTRUM: COLLECTION OF STATIONARY ATOMS

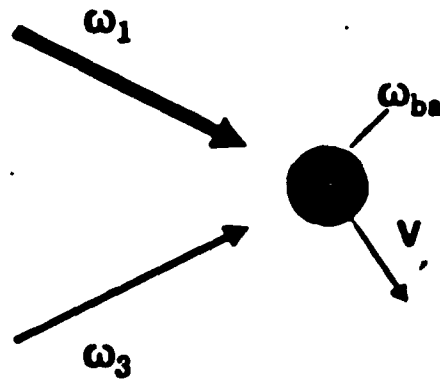


$$\Omega = 1.2 \text{ GHz} \quad T_2/T_1 = .28$$

$$\Delta = -1.3 \text{ GHz} \quad \alpha_0 L = 300$$

F. Y. Wu, S. Ezekiel, M. Ducloy, B. R. Mollow, Phys. Rev. Lett. **38**, 1077 (1977)

EFFECTS OF ATOMIC MOTION ON SINGLE-ATOM RESPONSE

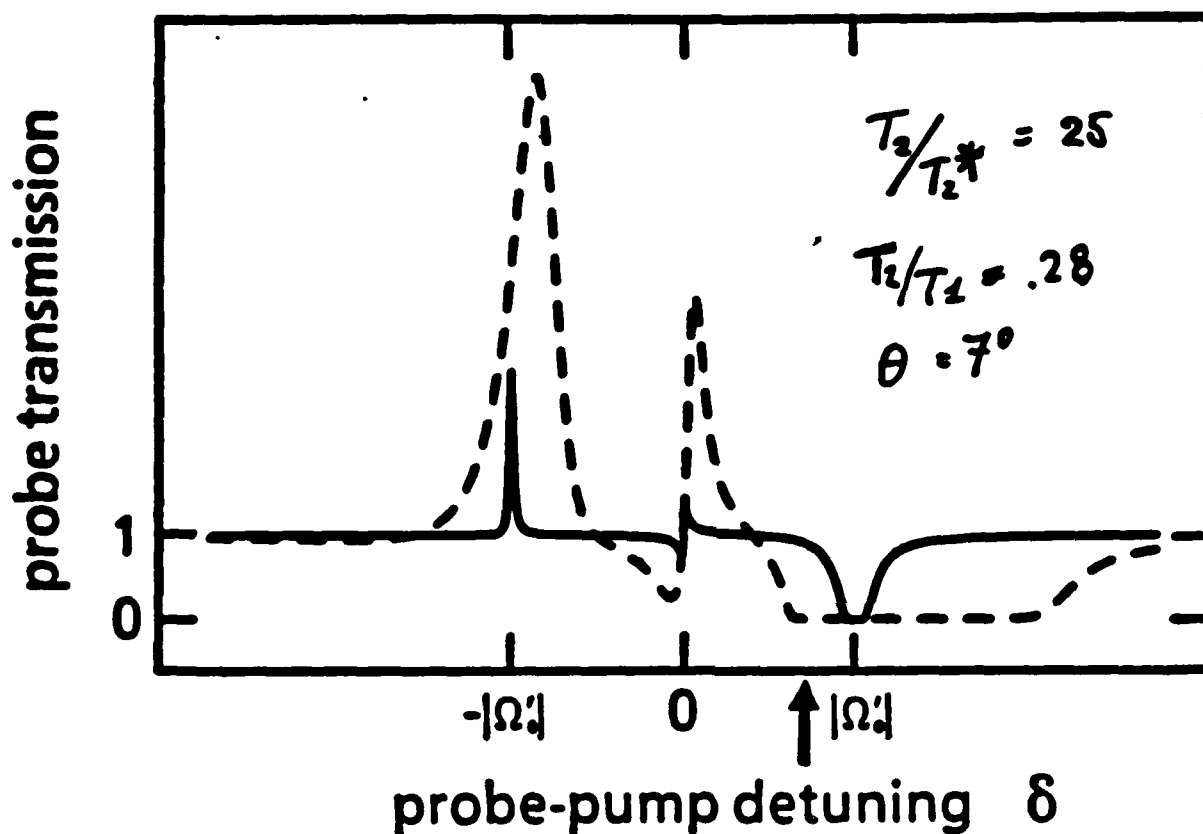


- In general, both $\Delta = \omega_1 - \omega_{ba}$ and $\delta = \omega_3 - \omega_1$ are velocity dependent.
- Doppler shift in Δ introduces velocity dependence in Ω' .
- For copropagating waves, there is no Doppler shift in $\delta = \omega_3 - \omega_1$.

General Expression for Amplitude Absorption Coefficient:

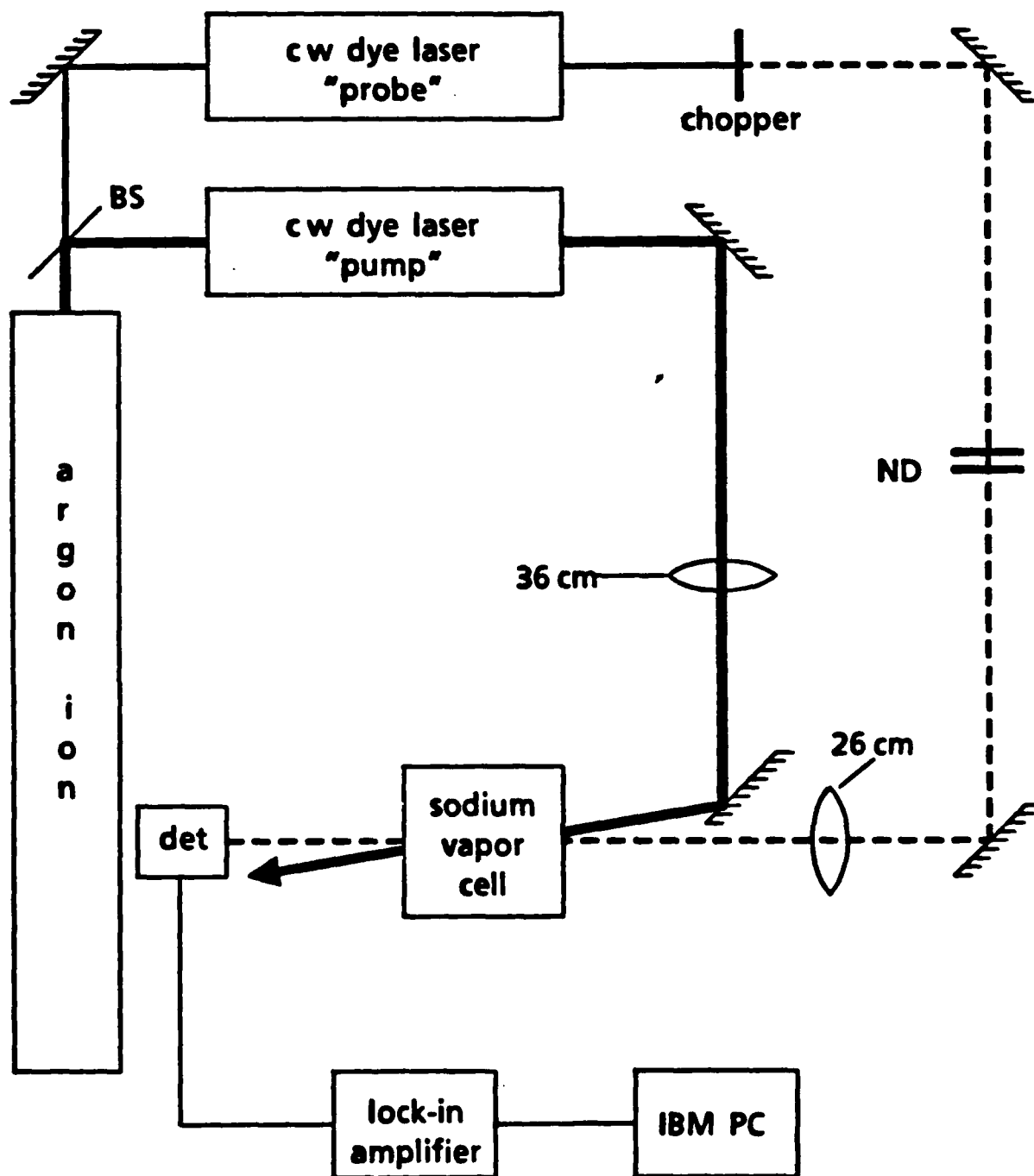
$$\alpha^D(\omega_3, \omega_1) = \left(\frac{n}{2\pi k_B T} \right)^{3/2} \iiint_{-\infty}^{+\infty} d^3v \, \alpha(\omega_3 + \mathbf{k}_3 \cdot \mathbf{v}, \omega_1 + \mathbf{k}_1 \cdot \mathbf{v}) \exp\left(-\frac{m|\mathbf{v}|^2}{2k_B T}\right)$$

PROBE TRANSMISSION SPECTRUM WITH DOPPLER BROADENING

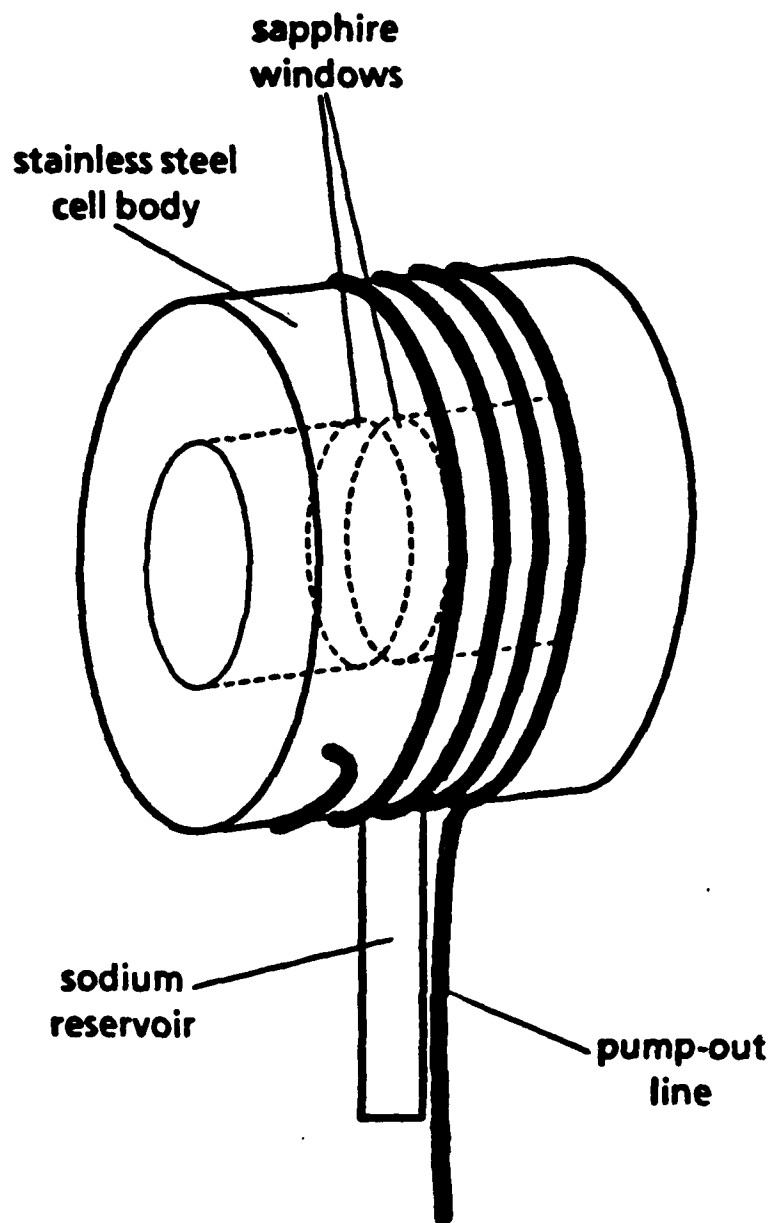


- Three-photon resonance is broadened to Doppler width.
- Three-photon resonance peak is "pulled" towards pump frequency.
- For nearly copropagating waves, the nearly degenerate lineshape remains narrow and increases in amplitude.

EXPERIMENTAL CONFIGURATION

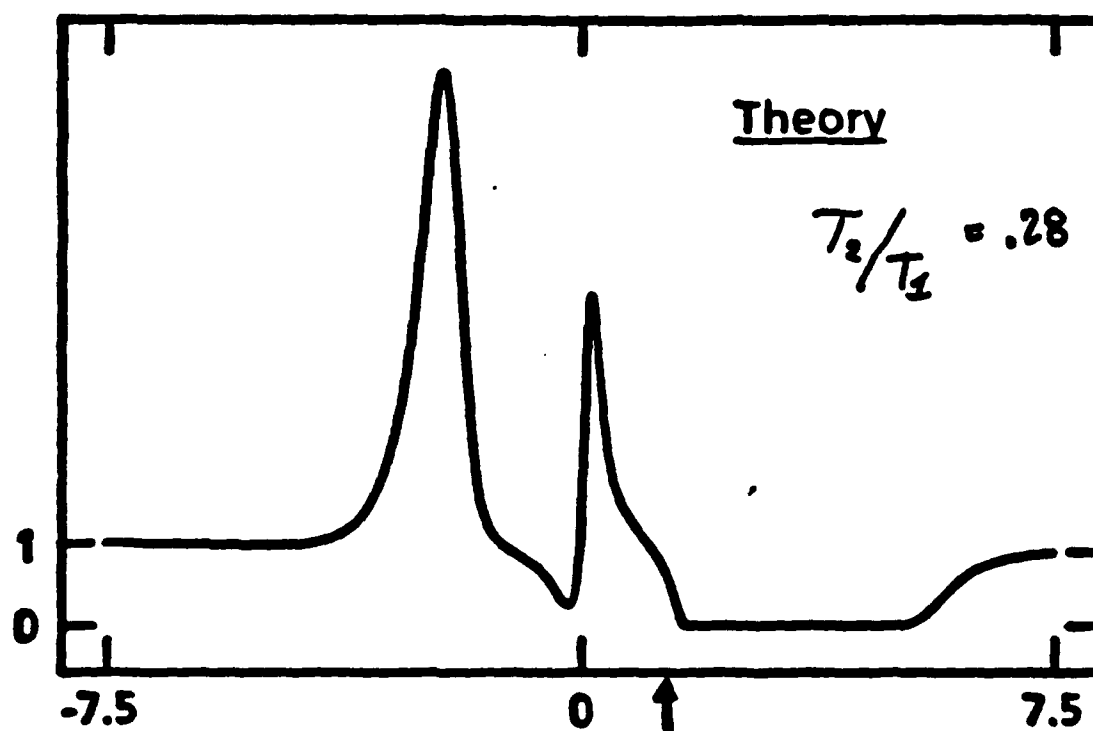


SODIUM VAPOR CELL

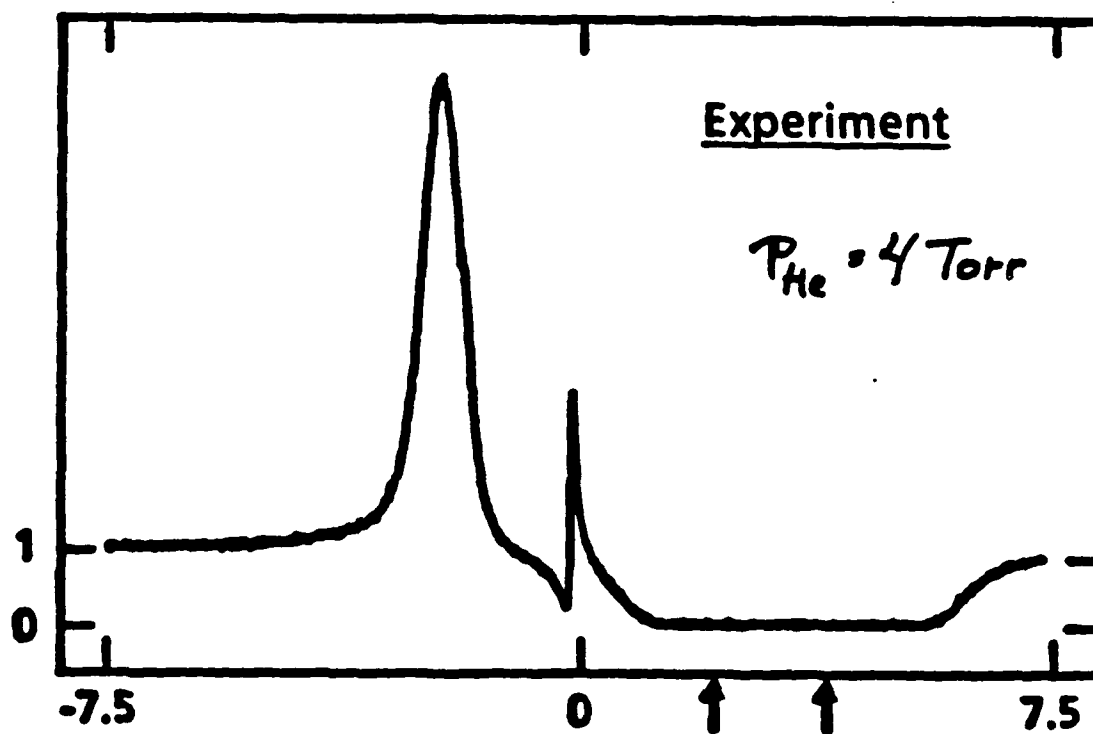


TRANSMISSION SPECTRA WITH DOPPLER BROADENING

probe transmission

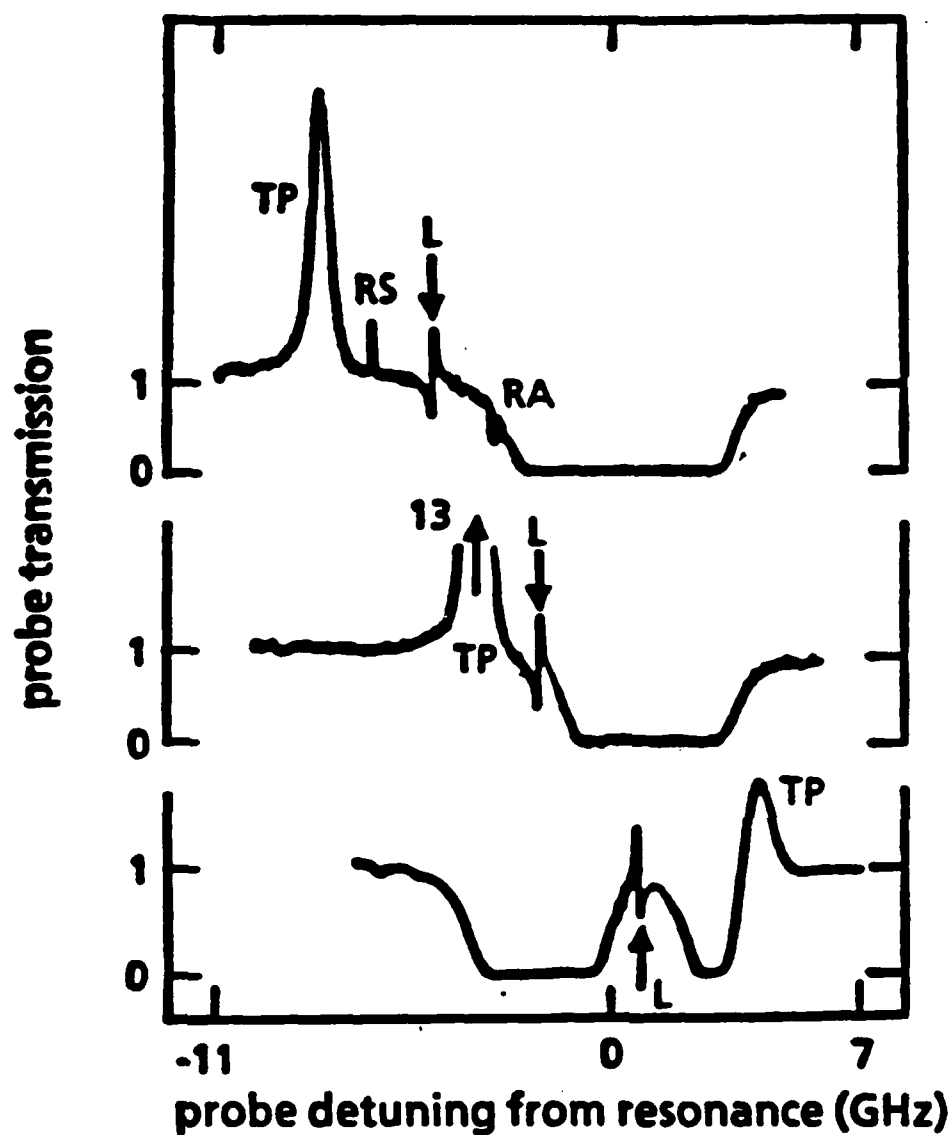


probe transmission



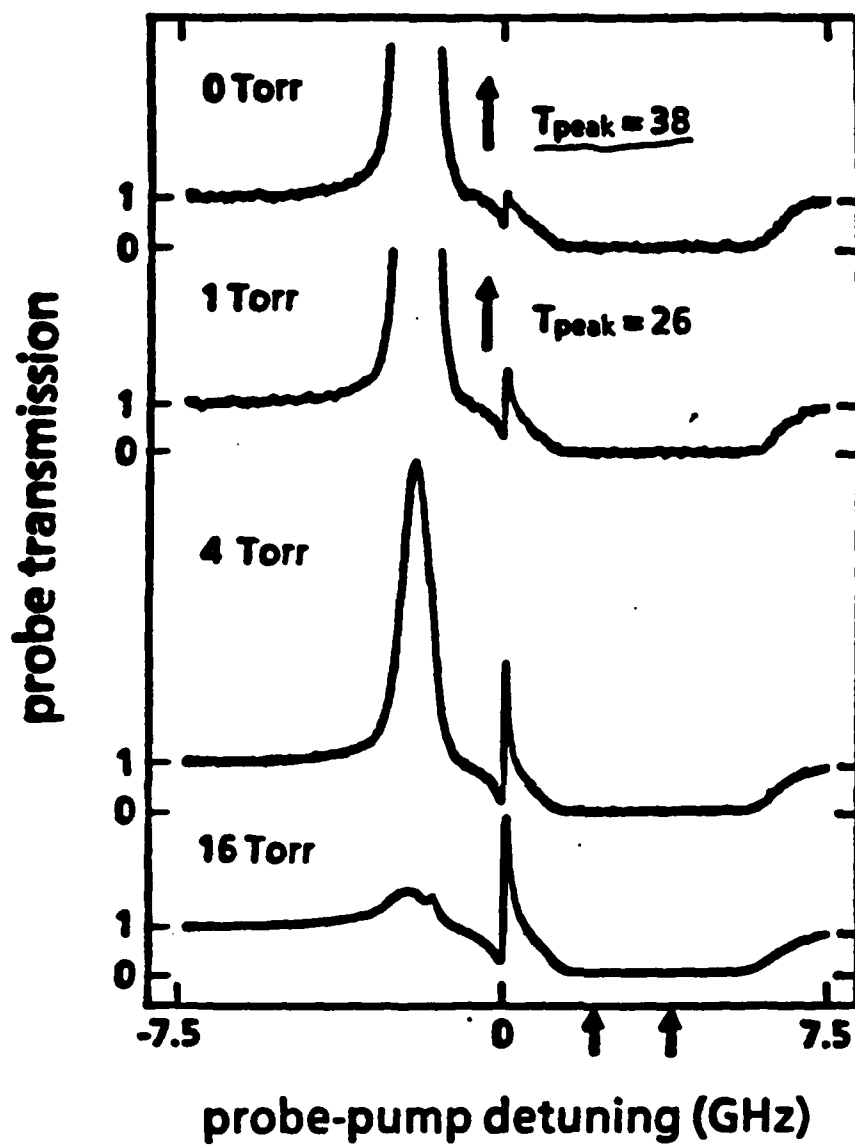
probe-pump detuning (GHz)

EFFECTS OF PUMP-LASER DETUNING



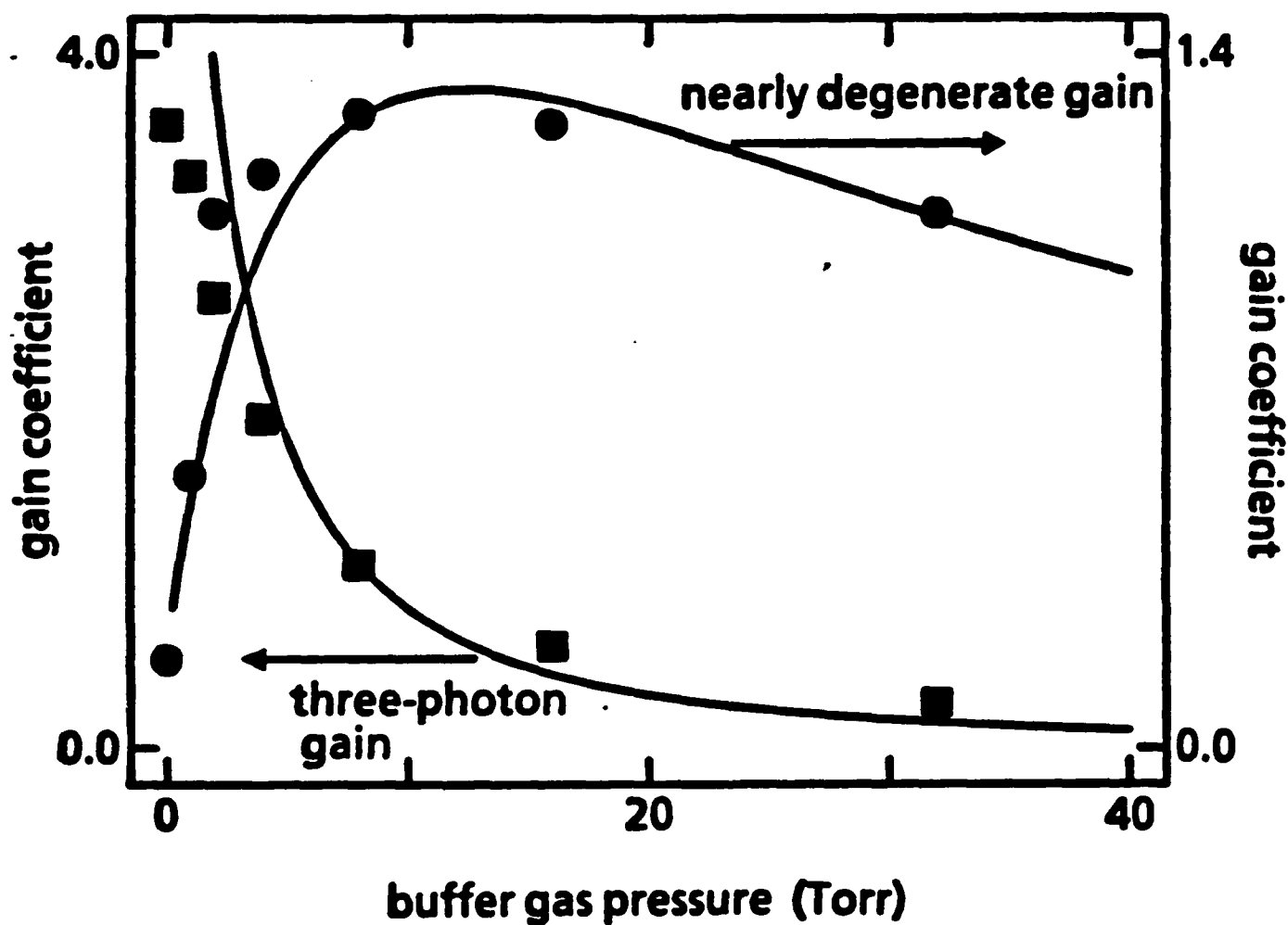
- Raman scattering from ground state hyperfine levels observed.
- Amplitude and location of three-photon peak vary with Δ .
- sign of α_{nd} and Ω' depend on sign of Δ .

EFFECTS OF COLLISIONAL DEPHASING



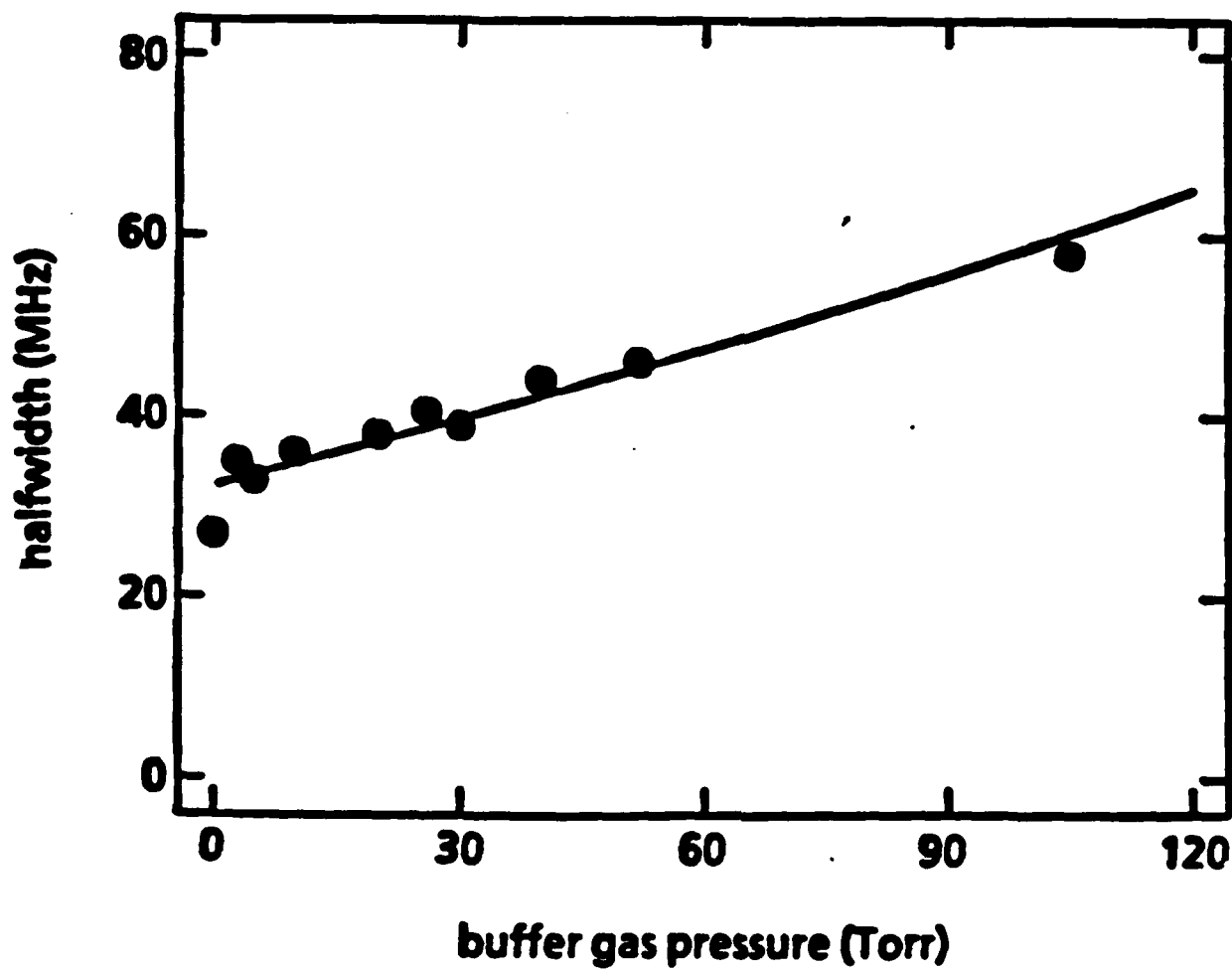
- Three-photon resonance diminishes rapidly with increased collisional dephasing.
- Amplitude of nearly degenerate resonance can be enhanced by collisional dephasing.

GAIN VS BUFFER GAS PRESSURE



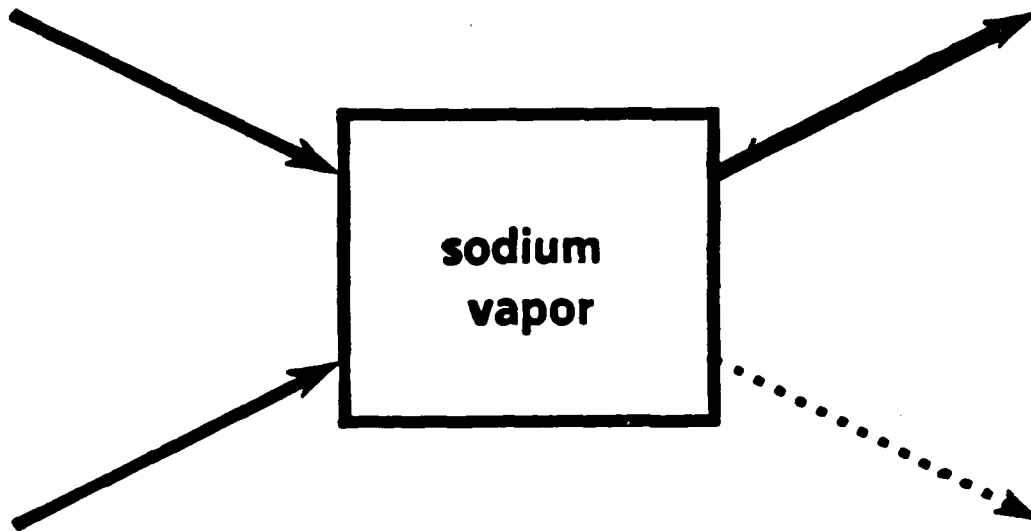
- Peak Three-photon gain occurs for zero buffer gas pressure.
- Nearly degenerate gain can be optimized by adding buffer gas.
- Single two-level atom theory can be used to describe functional dependence.

WIDTH OF NEARLY DEGENERATE RESONANCE VS BUFFER GAS PRESSURE



- At zero pressure, width is broadened to 30 MHz by atomic motion.
- width is broadened additionally by collisional dephasing.

LASER BEAM COMBINING IN SODIUM VAPOR



- Two-level atom
- propagation effects, atomic motion
- Limited coupling efficiency via three-photon effect
- High efficiency coupling at nearly degenerate feature

CONTINUED FRACTION SOLUTION TO OPTICAL BLOCH EQUATIONS*

Strong field absorption coefficient:

$$\alpha_2 = D_2 \{ \alpha - [Re(\kappa) - (\delta\omega + \gamma)T_2 Im(\kappa)] I_1 \}$$

where

$$\alpha = \frac{\alpha_0}{1 + D_1(I_1 + I_2) - 2|I_c|^2 Re\{K_0 L_1 F\}}$$

and

$$\kappa = L_1 F \alpha$$

with

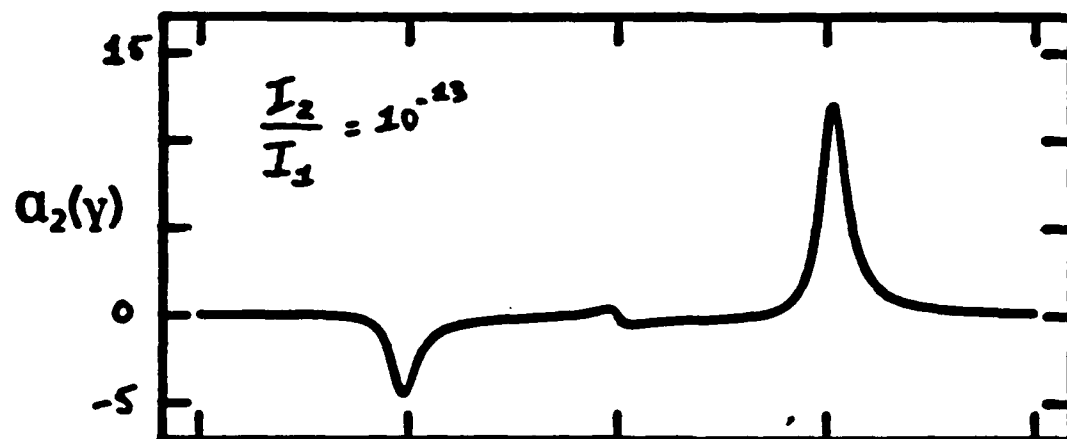
$$\begin{aligned} & 1 \\ & \hline 1 + M_1 I_1 + N_1 I_2 - i\gamma T_1 - \frac{K_1 L_2 |I_c|^2}{1 + M_2 I_1 + N_2 I_2 - i2\gamma T_1 + \frac{K_2 L_3 |I_c|^2}{1 + M_3 I_1 + N_3 I_2 - i3\gamma T_1 - \frac{K_3 L_4 |I_c|^2}{1 + M_4 \dots}}} \end{aligned}$$

A. L. Gaeta, unpublished

L. W. Hillman, J. Krasinski, K. Koch, and C. R. Stroud, J. Opt. Soc. Am. B 2, 211 (1985)

G. S. Agarwal and N. Nayak, J. Opt. Soc. Am. B 1, 164 (1984)

INTENSE FIELD ABSORPTION SPECTRUM

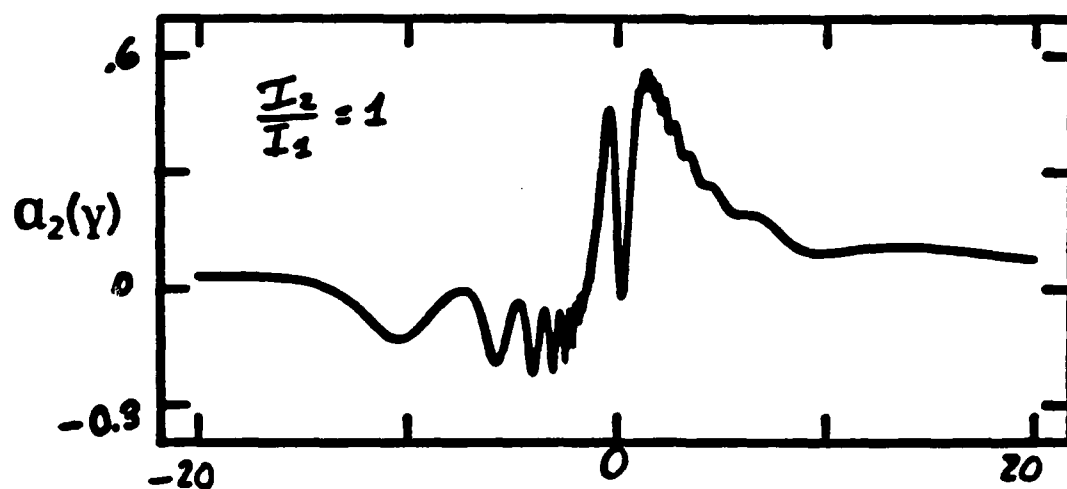
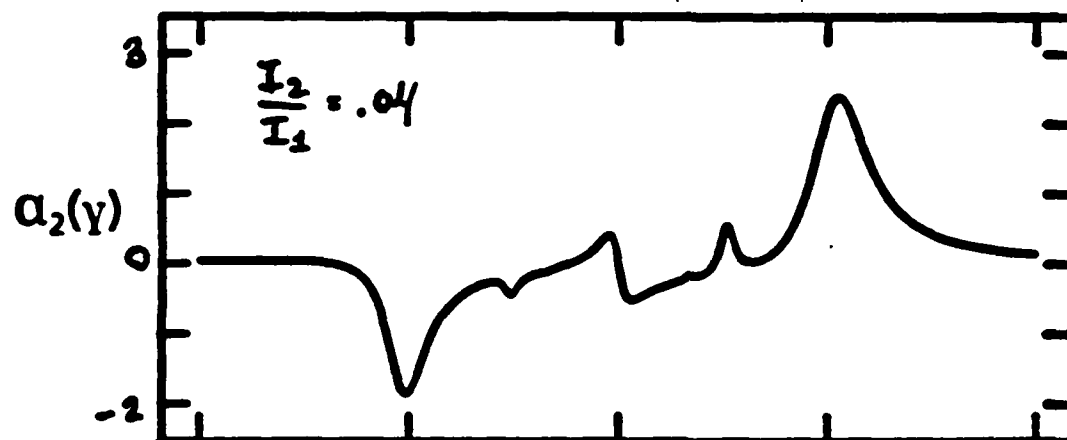


$$\Omega_2 T_2 = 10$$

$$\alpha_0 L = 100$$

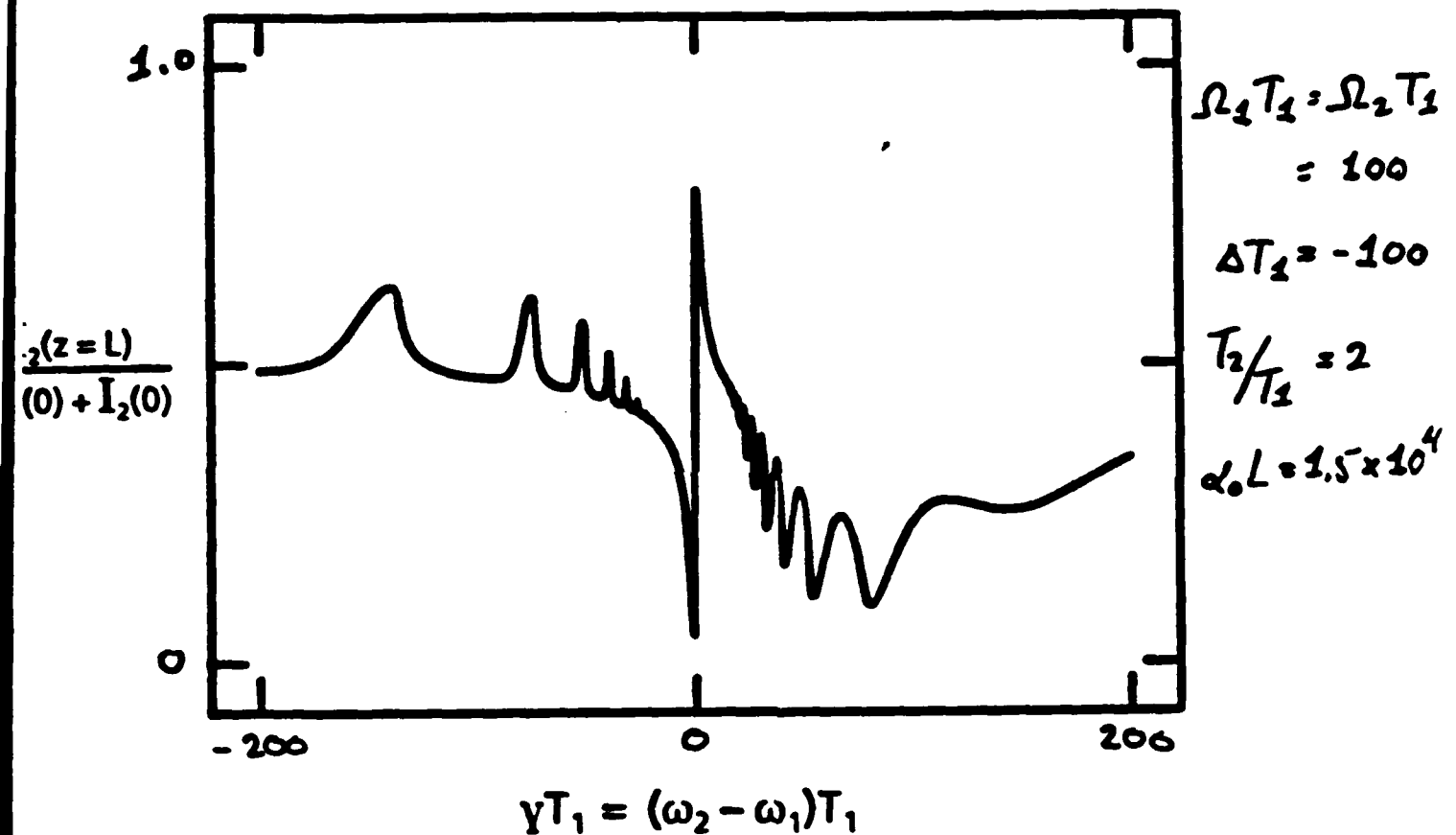
$$T_2/T_1 = 2$$

$$\Delta T_2 = -2.5$$



$$\gamma T_1 = (\omega_2 - \omega_1)T_1$$

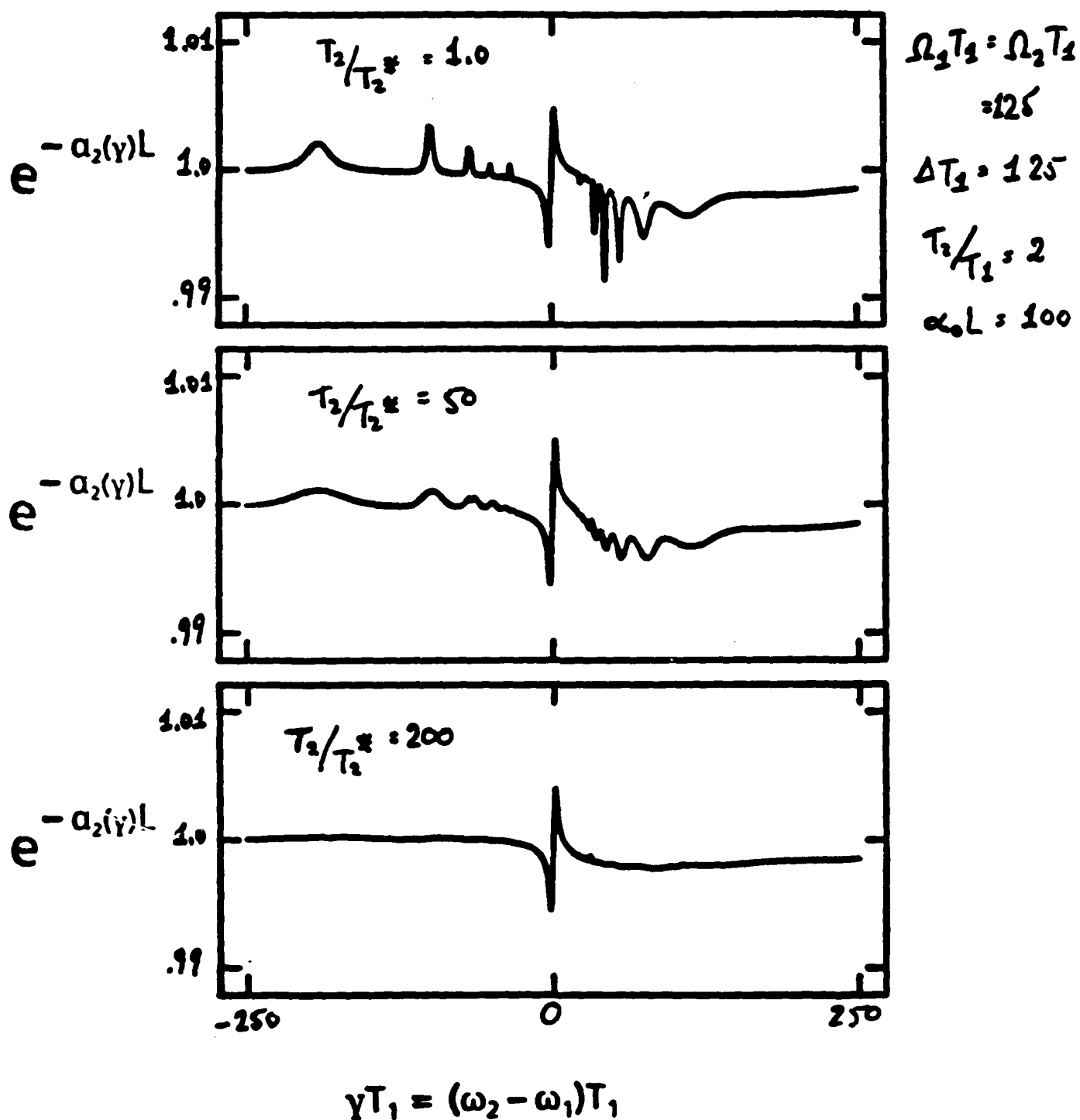
TRANSMISSION SPECTRUM WITH PROPAGATION EFFECTS



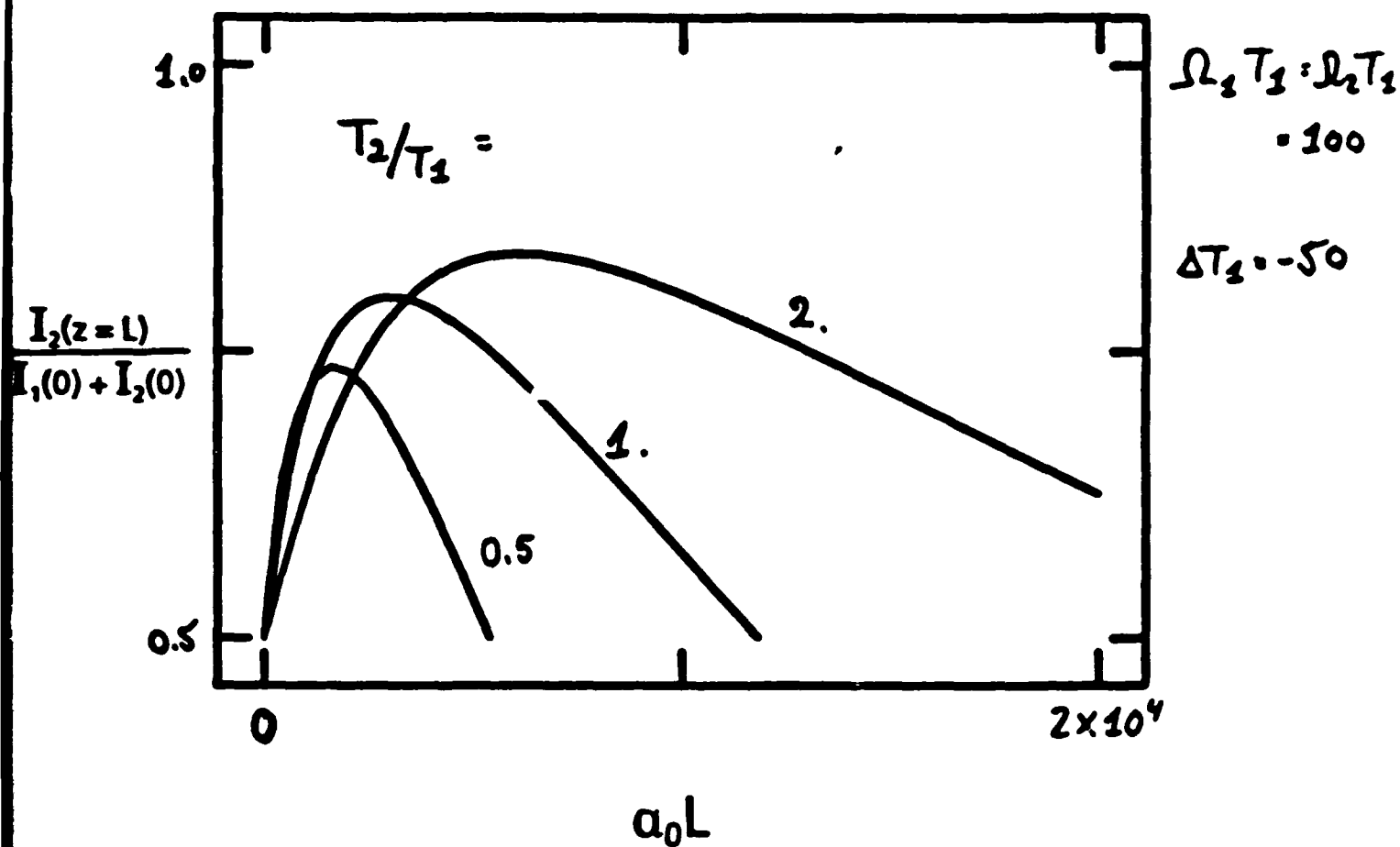
- Define coupling efficiency: $0 \leq \frac{I_2(z=L)}{I_1(0) + I_2(0)} \leq 1$
- Nearly degenerate feature provides most efficient coupling.
- Three-photon coupling is limited by:
 1. propagation – Ω' changes due to depletion.
 2. excitation – scattering process requires two pump photons.

EFFECTS OF DOPPLER BROADENING

● Neglect propagation effects

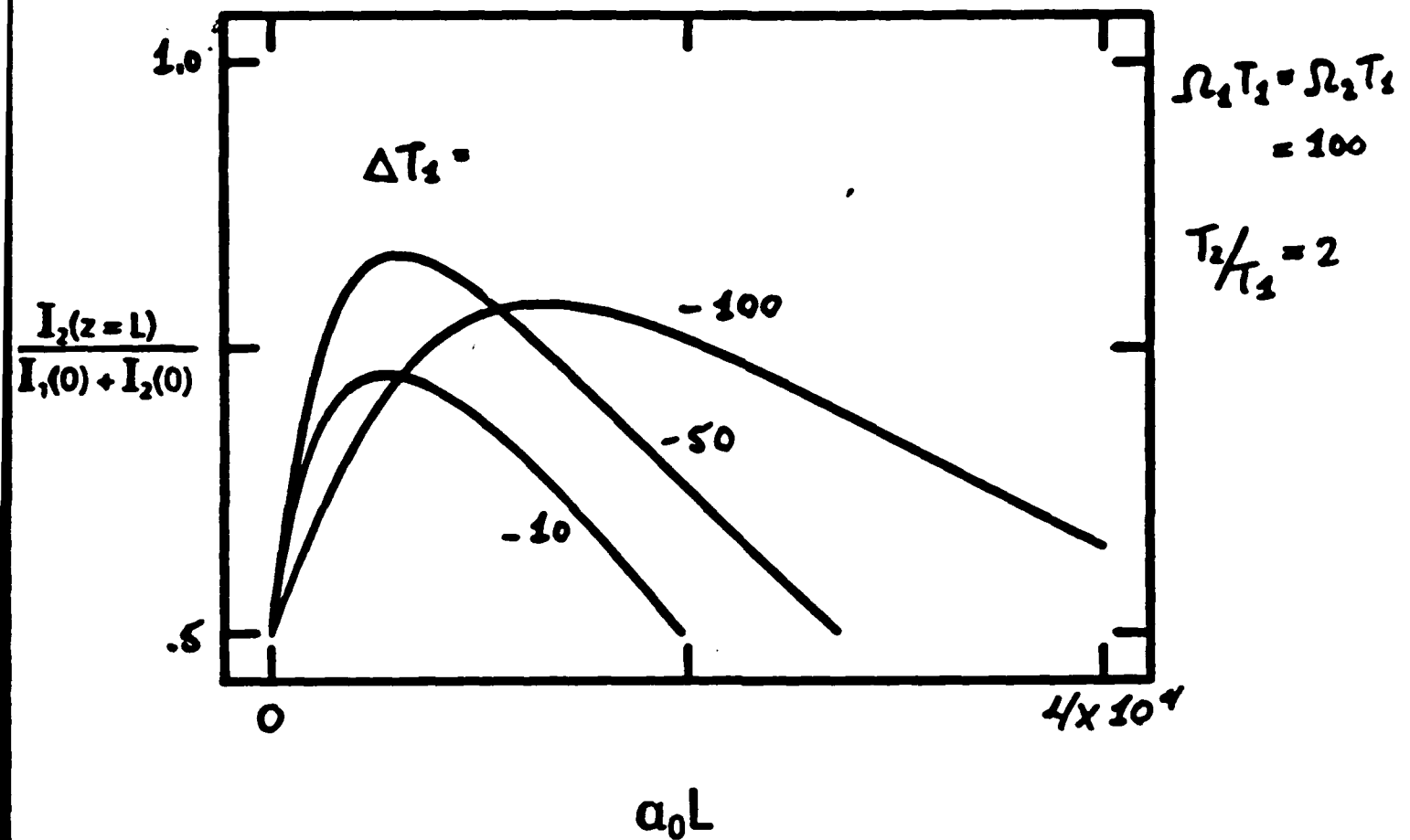


NEARLY DEGENERATE COUPLING EFFECTS OF COLLISIONAL DEPHASING



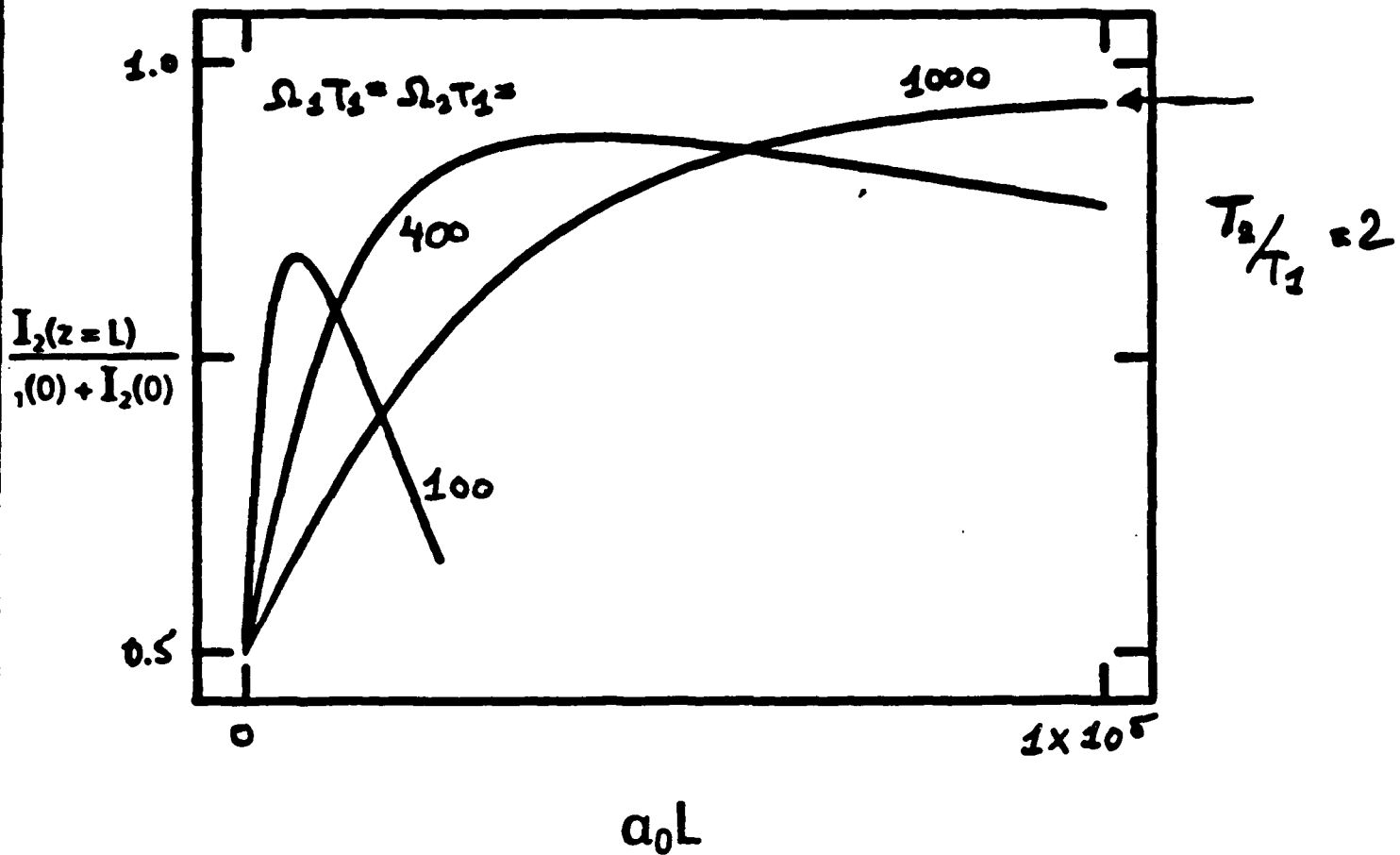
- At low a_0L , choose $T_2/T_1 < 2.0$
- At high a_0L , choose $T_2/T_1 = 2.0$

NEARLY DEGENERATE COUPLING EFFECTS OF DETUNING



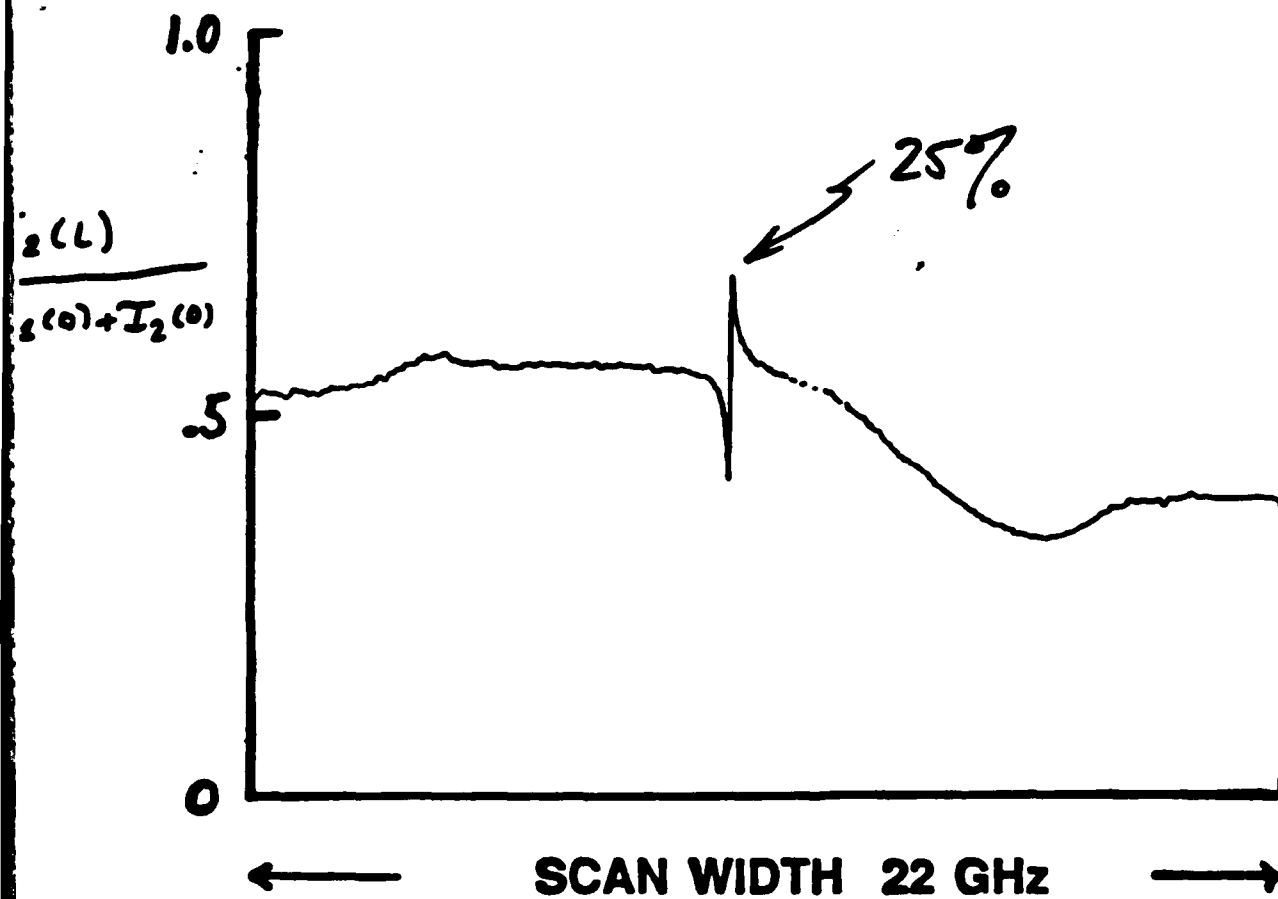
- For low $\alpha_0 L$, tune near resonance.
- For large $\alpha_0 L$, tune away from resonance to avoid absorption losses.
- Choose $\Delta = \Omega/2$ to optimize coupling.

NEARLY DEGENERATE COUPLING EFFECTS OF LASER INTENSITY



- High coupling efficiency requires:
 - $T_2/T_1 \approx 2.0$
 - $a_0L > 10^5$
 - $\Omega_1 T_1 > 10^3$

BEAM COMBINING DATA



$$I_1 = 450 \text{ W/cm}^2 \Rightarrow \Omega_1 T_1 = 380$$

$$I_2 = 600 \text{ W/cm}^2 \Rightarrow \Omega_2 T_2 = 435$$

$$T = 230^\circ\text{C}$$

$$N \approx 10^{18} / \text{cm}^3$$

$$P_{He} = 10 \text{ Torr}$$

$$\alpha_0 L \approx 10^3$$

SUMMARY

Part I: probe beam amplification

I. Observed probe wave amplification in a strongly driven atomic vapor

A. Three-photon effect

- 1. measured large amplification: $G = 38$**
- 2. gain diminishes rapidly with collisional dephasing**

B. Nearly Degenerate Coupling

- 1. measured amplification of $G = 4$ at $P_{He} = 10$ Torr**
- 2. feature is "robust" in presence of collisional dephasing**

II. Theoretical modeling

A. Stationary two-level atom theory accurately models gain dependence on buffer gas pressure

B. Numerical average over a Maxwell velocity distribution accounts for effects of atomic motion

Part II: beam combining

I. Treated analytically by continued fractions

A. Three-photon effect

- 1. diminishes with Doppler broadening**
- 2. propagation effects reduce coupling efficiency**
- 3. coupling efficiency is inherently limited**

B. Nearly degenerate resonance

- 1. insensitive to Doppler broadening (copropagating waves)**
- 2. large coupling efficiencies are possible**

II. Experimental results

A. ~~20%~~ energy transfer measured to date 25%

- 1. intensity limited**
- 2. experiment in progress**

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
APPLICATIONS OF PHASE CONJUGATION

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
OPTICAL PHASE CONJUGATION IN PHOTOREFRACTIVE MATERIALS

LASER RESEARCH TEAM:

R & D of nonlinear optical materials, techniques, and concepts

- Beam Control Devices
 - Optical Switches
 - Optical Isolators
 - Filters
- Laser Components
 - New Sources
 - Q-Switches
 - Modulators

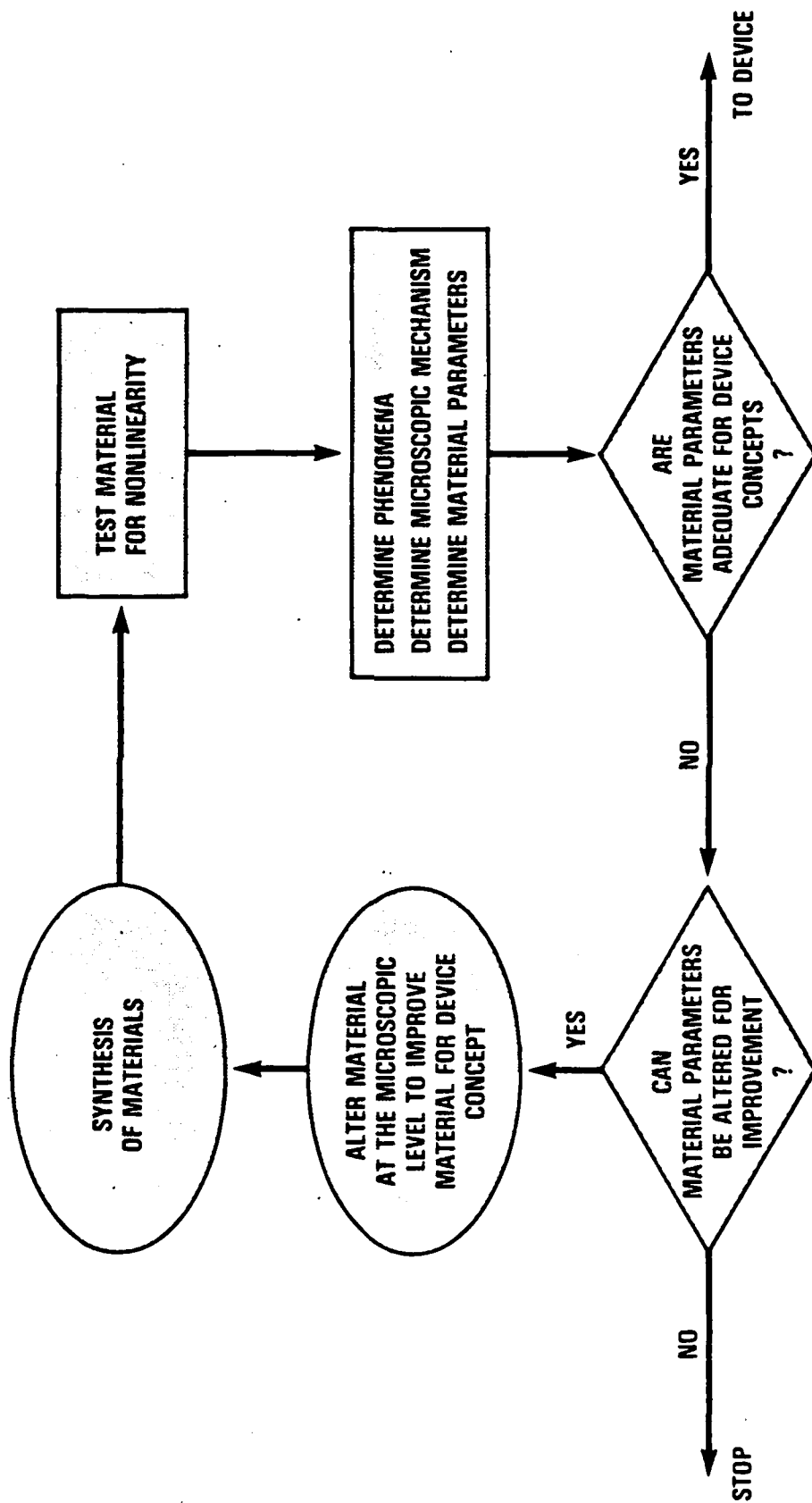
RECENT RESEARCH ACTIVITY

- Tungsten-Bronze Family of Ferroelectric Crystals (SBN & BSKNN)
 - Ferroelectric Properties (Sensors)
 - Electro-Optic Properties (Broad-Band Modulators)
 - Photorefractive Properties
 - Optical Isolation of Coherent Beams Via Beam Fanning and Two-Beam Coupling
 - Phase Conjugation for Image Processing (Amplification, Storage, and Enhancement)

KEY ISSUES

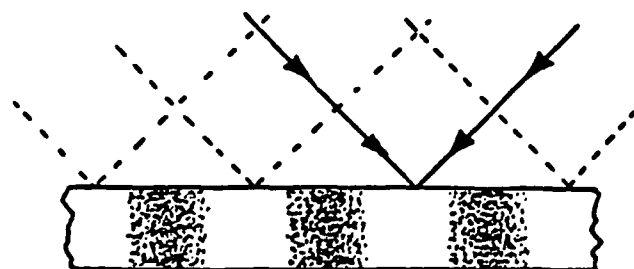
- O TIME RESPONSE**
- O SENSITIVITY**
- O SPECTRAL BANDWIDTH**
- O MATERIAL AVAILABILITY/QUALITY**
- O MATERIAL IMPROVEMENTS**
- O POSSIBILITY FOR NEW DEVICES**

NONLINEAR OPTICAL MATERIALS EFFORT



"WONDERS"

- 0 Δn is large ($\sim 10^{-3}$)
- 0 Δn depends on energy and not on intensity
- 0 time to achieve Δn depends on intensity



INTERFERING
COHERENT BEAMS

PHOTOREFRACTIVE
MEDIUM

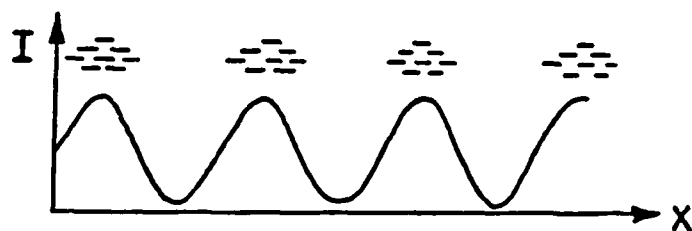
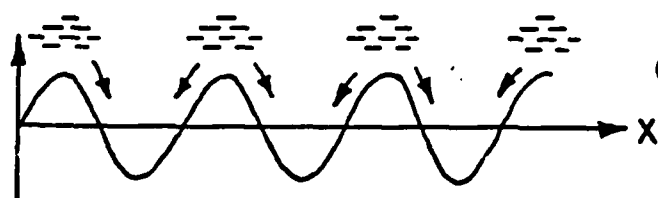


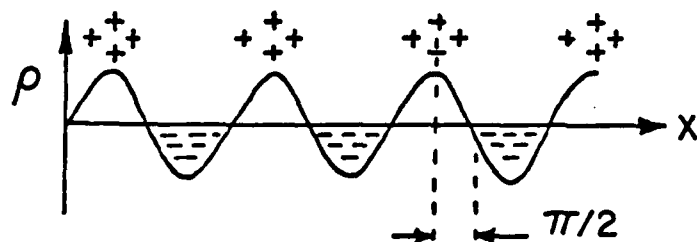
PHOTO-EXCITED
CARRIERS

INTENSITY PATTERN (a)



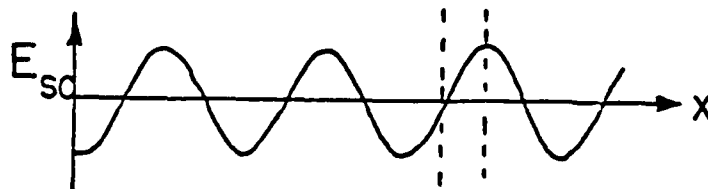
CHARGE TRANSPORT
(DIFFUSION)

(b)



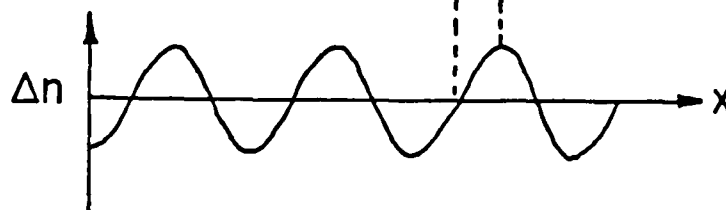
SPACE CHARGE
DISTRIBUTION

(c)



SPACE CHARGE FIELD
 $\nabla \cdot E \sim \rho$

(d)

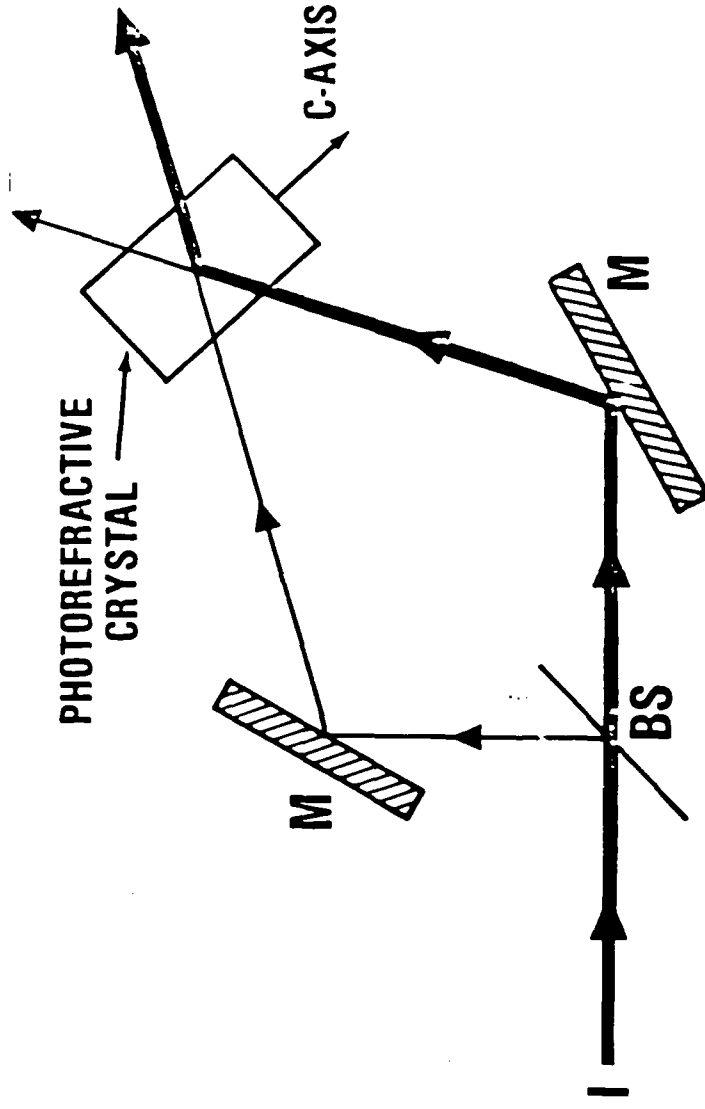


INDEX GRATING
 $\Delta n \sim r E_{sc}$

(e)

Fig 1

TWO BEAM COUPLING

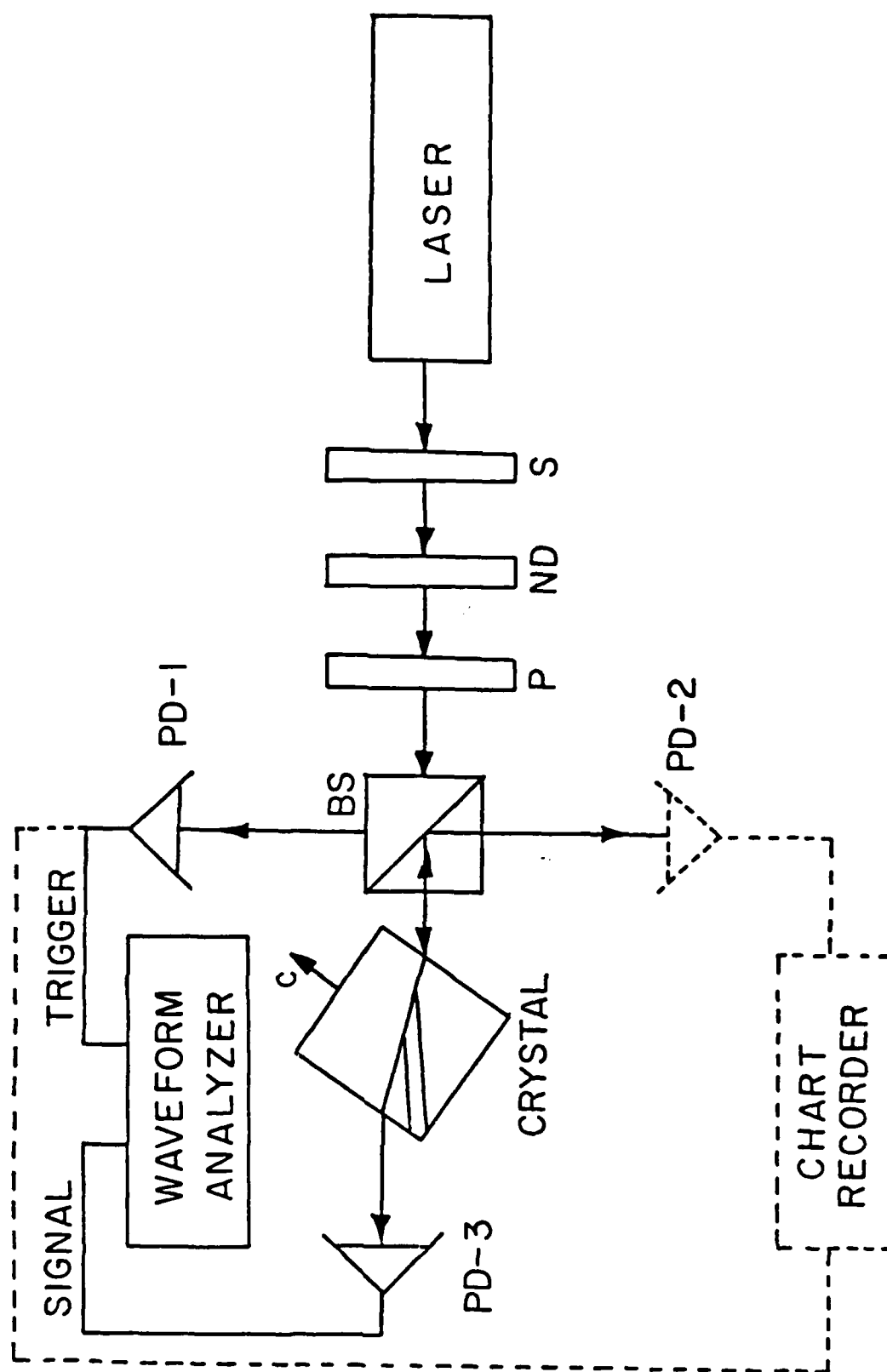


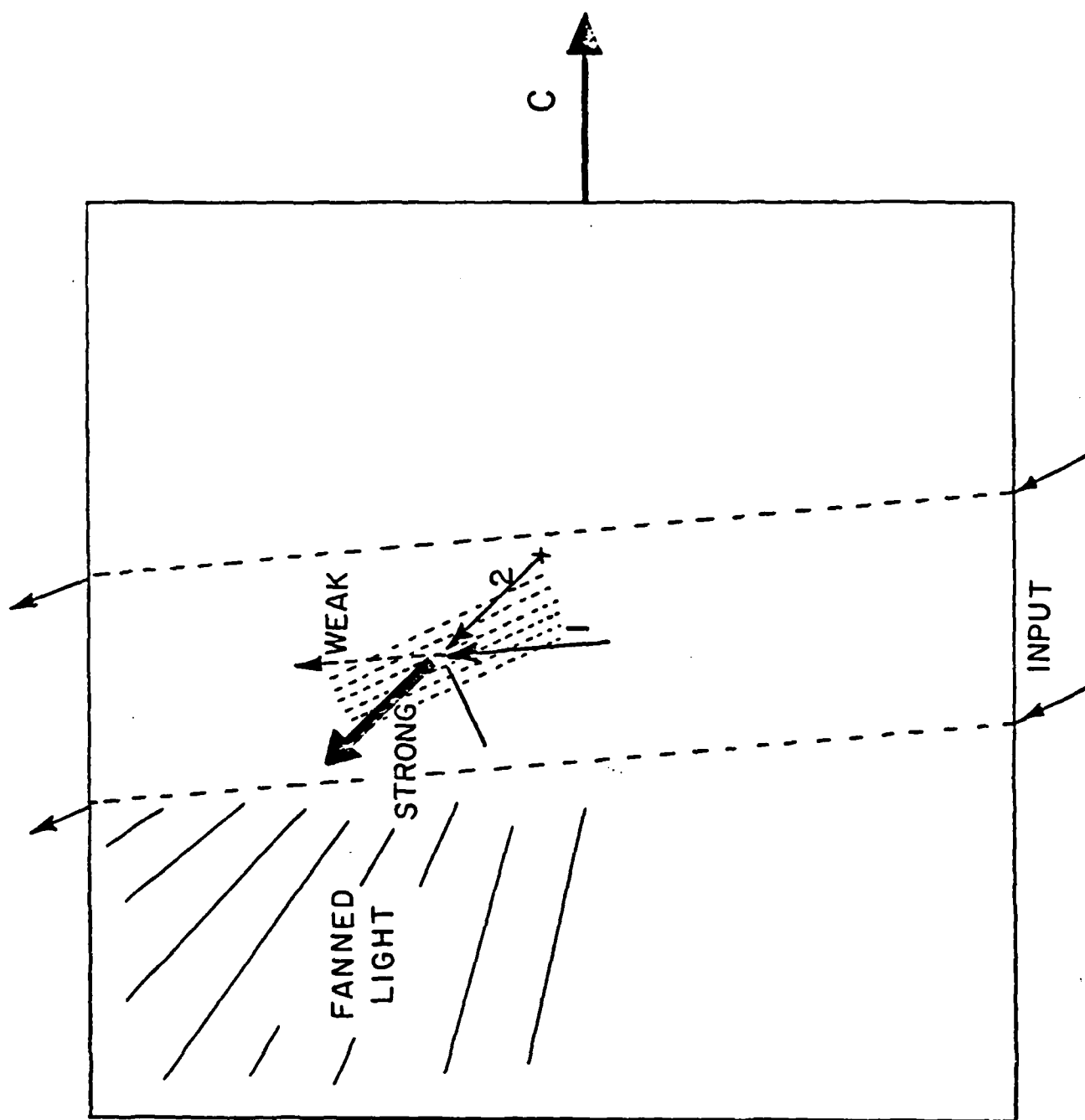
KEY FEATURES: • LARGE INDEX CHANGES FOR MILLIWATT BEAMS

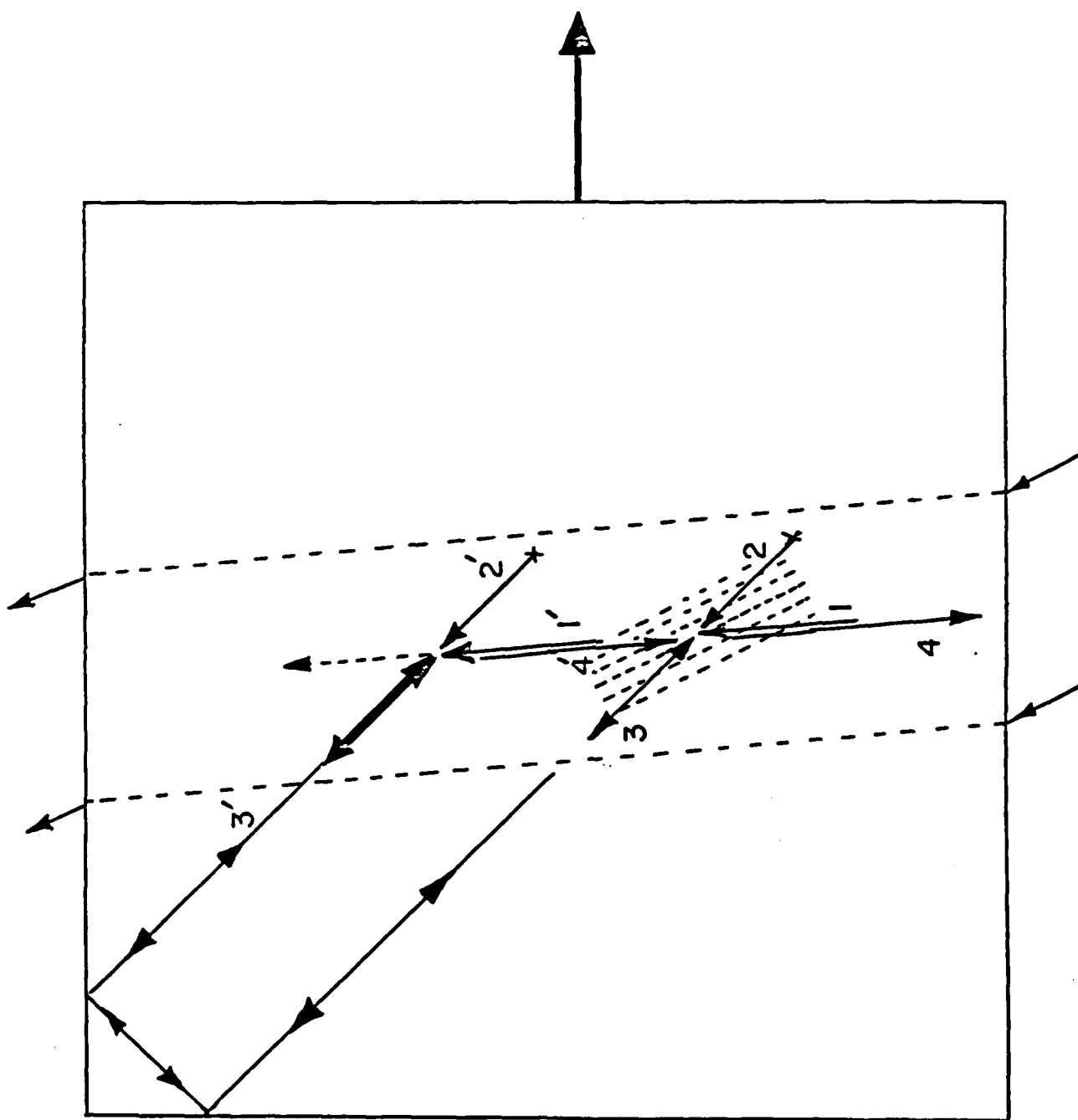
• INDEX GRATING IS SHIFTED 90° WITH RESPECT TO THE INTENSITY INTERFERENCE PATTERN

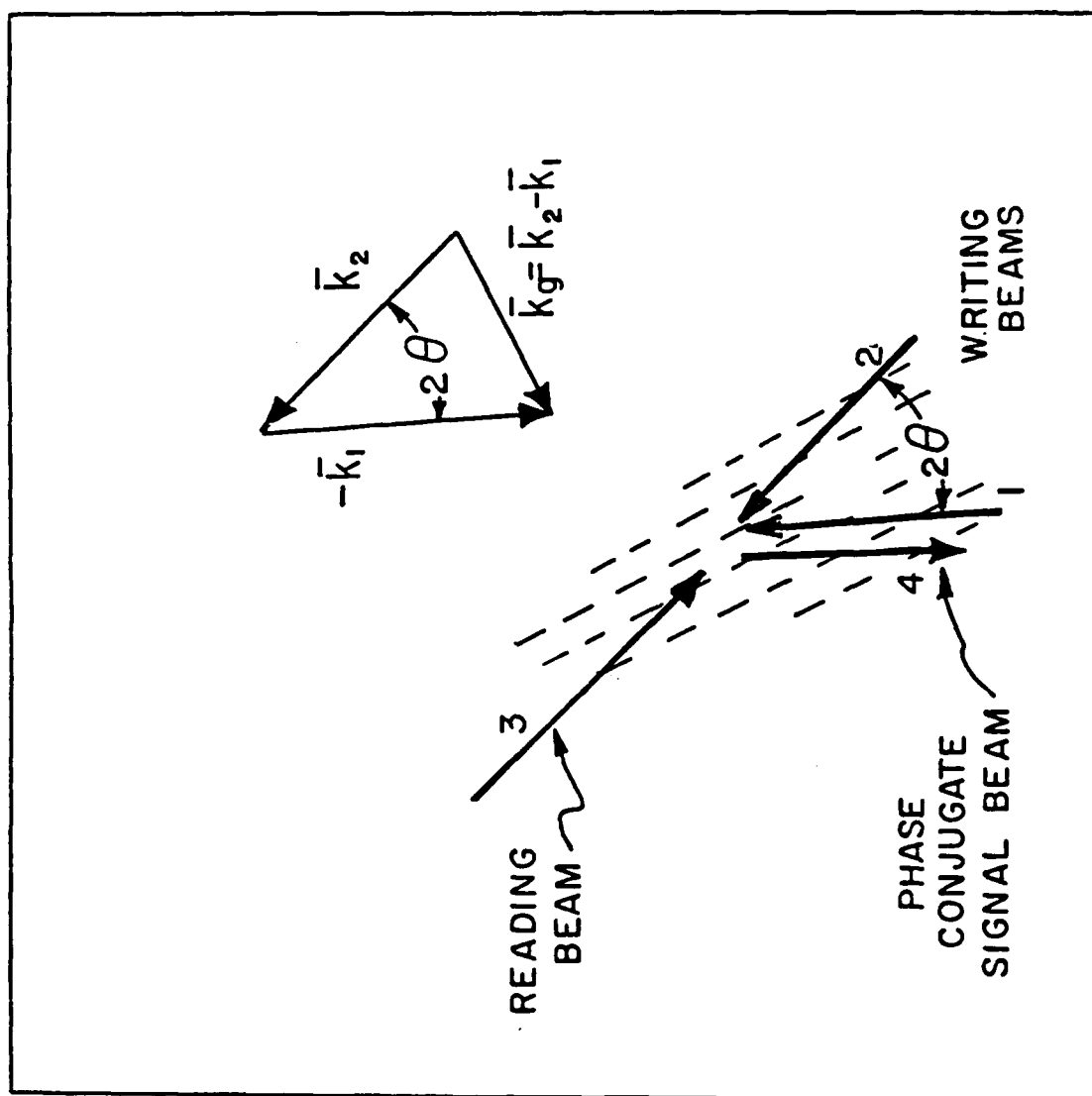
THEREFORE:

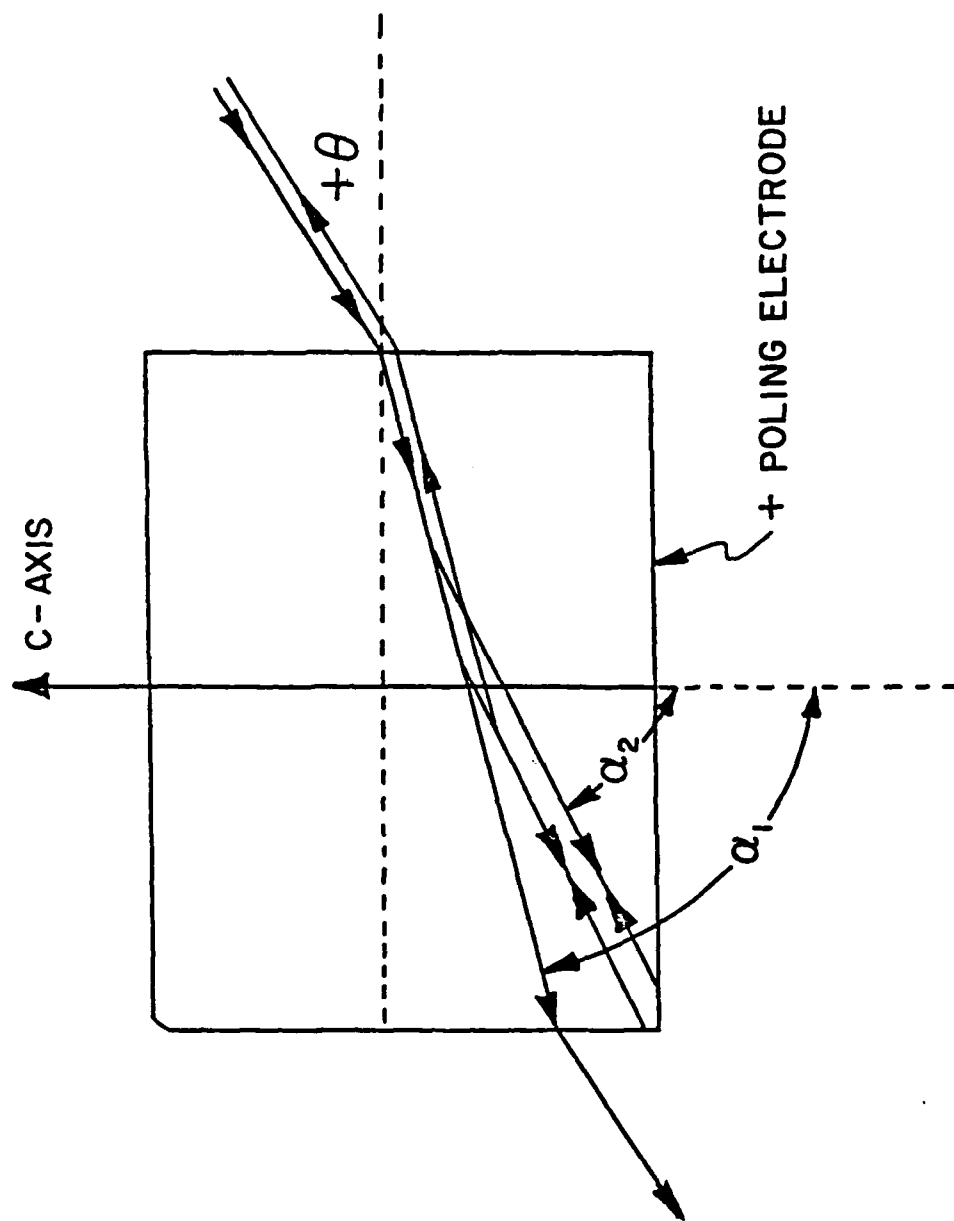
STRONG ENERGY EXCHANGE BETWEEN THE TWO BEAMS CAN OCCUR IN THE CRYSTAL SO THAT A WEAK BEAM CAN BE AMPLIFIED AT THE EXPENSE OF A STRONG BEAM

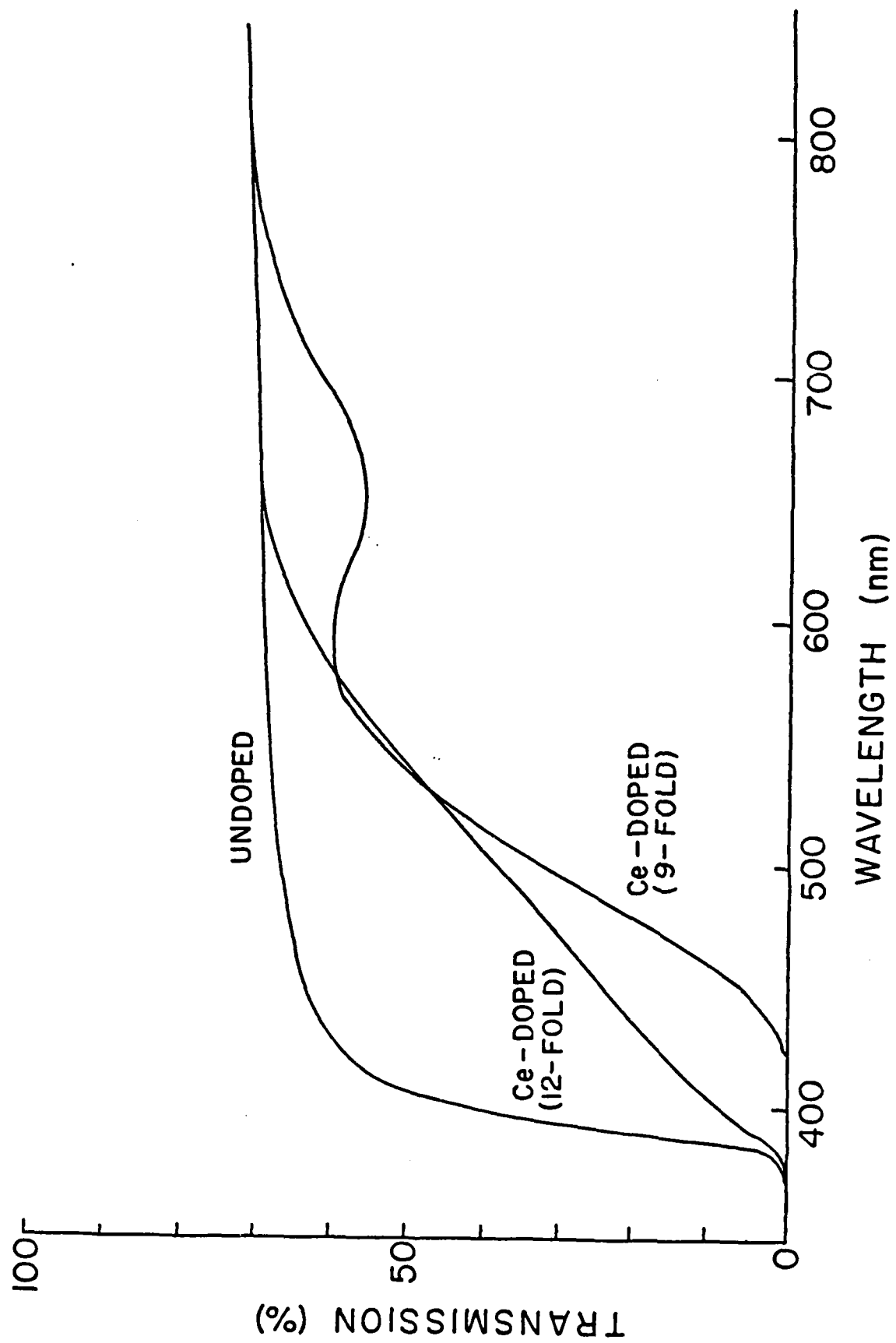










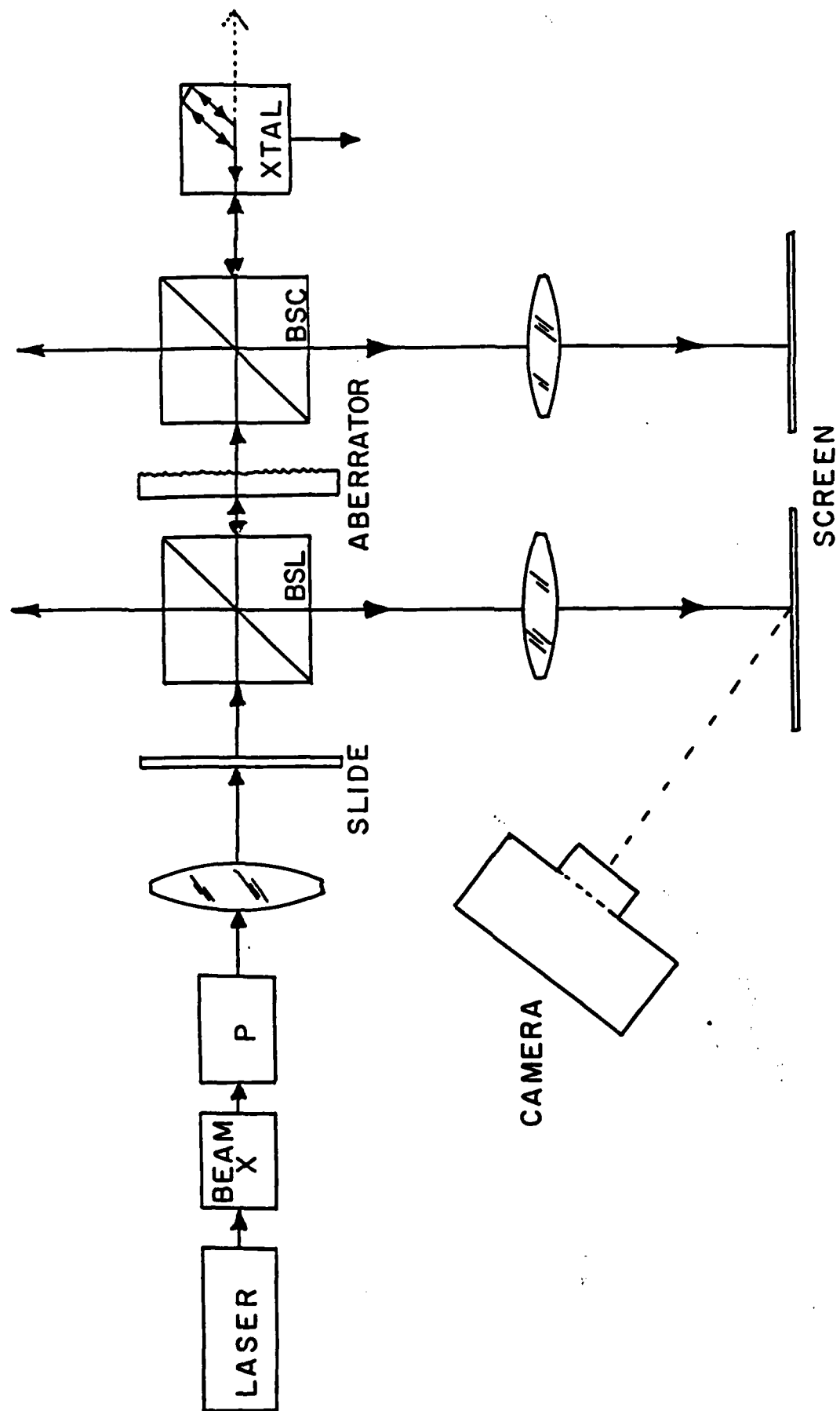


PROPERTY		SBN: 60	Ce-SBN: 60
DIELECTRIC CONSTANT	ϵ_{11}	= 470	= ---
	ϵ_{33}	= 880	= 1100
ELECTRO-OPTIC COEFFICIENT X 10^{-12} m/V	r_{13}	= 55	r_{13} = 55
	r_{33}	= 224	r_{33} = 244
	r_{42}	= 80	r_{42} = 80
REFRACTIVE INDEX (514.5 nm)	n_o	= 2.367	n_o = 2.346
	n_e	= 2.337	n_e = 2.310
BIREFRINGENCE $\Delta n = n_e - n_o$	Δn	= -0.03	Δn = -0.036
T_c (C°)		75	72
PHOTOREFRACTIVE SENSITIVITY (Cm^2/J)			
		3.2×10^{-5}	6.5×10^{-3}
RESPONSE TIME (ms)		1000	80
GROWTH TEMPERATURE (C°)		1500	1485
GROWTH DIRECTION		[001]	[001]
COLOR OF CRYSTAL		PALE CREAM	PINK

MATERIAL	WAVELENGTH RANGE OF INVESTIGATION (nm)	WAVELENGTH ¹ (nm)	SELF-PUMPED REFLECTIVITY (%)	TIME RESPONSE (sec)		Intensity
				Conjugate	Fan	
SBN: 60						
Undoped	442	442	60	---	---	---
Ce-doped	442-633	442	30	---	0.6	0.2 W/cm ²
				---	0.05	2 W/cm ²
Ce-doped ²	488-730	647	8	120	---	2 W/cm ²
SBN: 75						
Ce-doped	442-515	442	6	7.7	2.0	0.2 W/cm ²
				1.6	0.25	2 W/cm ²
BSKNN II						
Ce-Doped	458-515	458	30	279.5	5.8	0.2 W/cm ²
				88.4	0.9	2 W/cm ²
BSKNN III						
Ce-doped ²	488-780	647	20	1200	---	0.2 W/cm ²
				300	---	2 W/cm ²

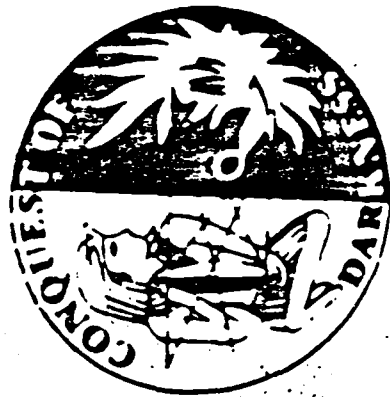
¹ This is the wavelength at which the data was taken

² Doping consists of cerium in 12-fold coordinated sites except in the cases marked with a 2 where cerium is in the 9-fold coordinated sites





INPUT



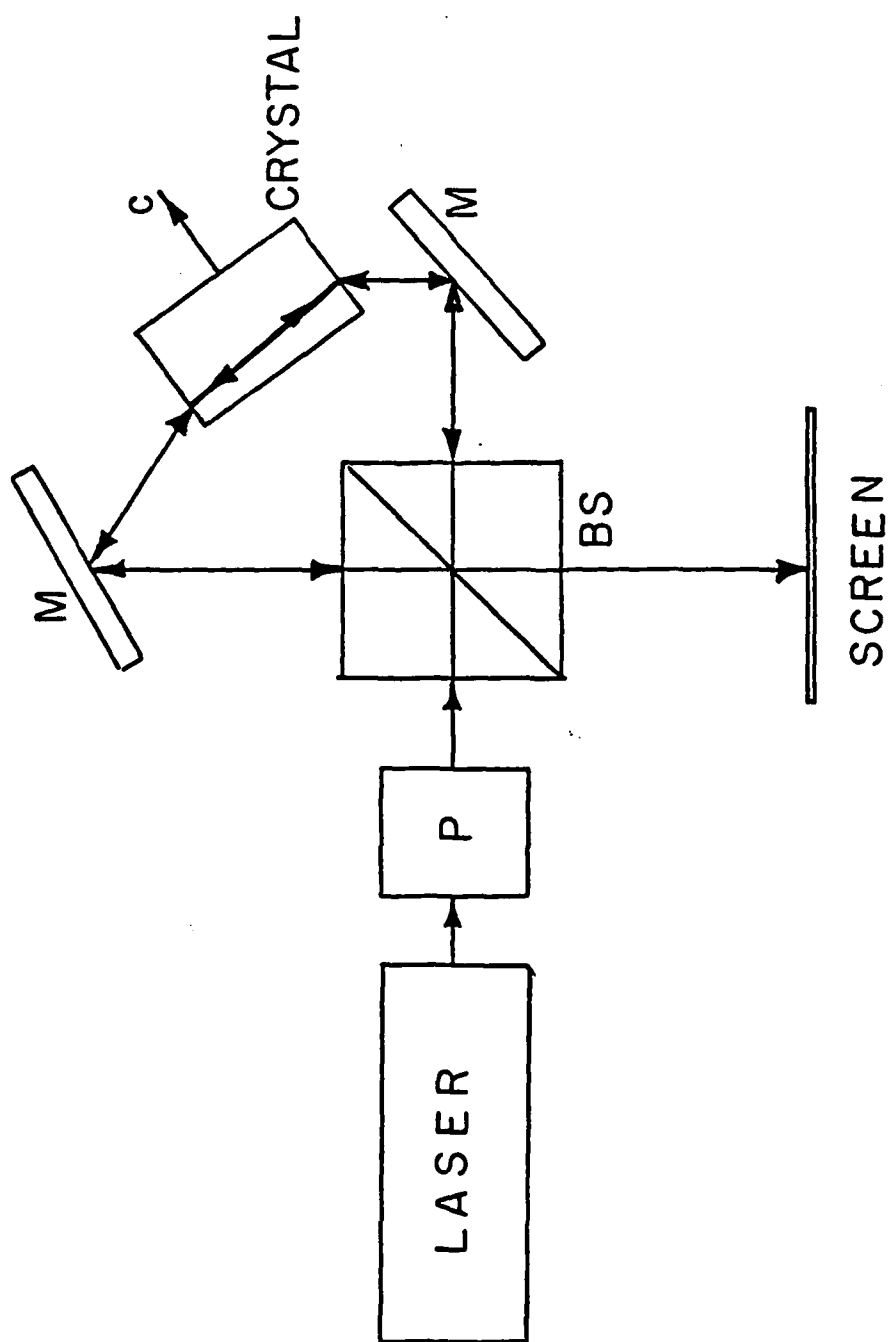
CONJUGATE

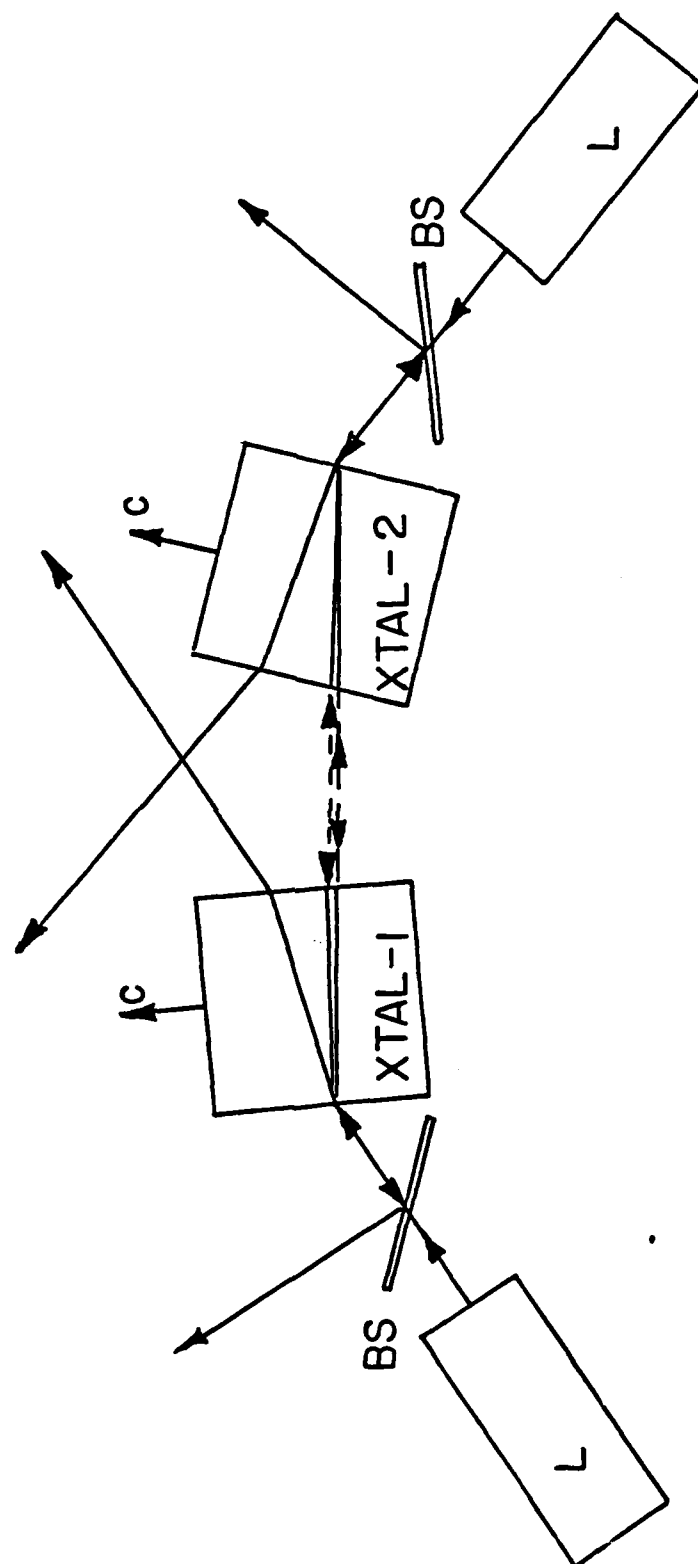


ABERRATED

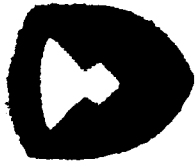


CORRECTED





**CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
STIMULATED BRILLOUIN SCATTERING FOR DIRECTED ENERGY LASERS**



PHASE COHERENCE TECHNOLOGY EVOLUTION

1972:

- FIRST DISCOVERED IN THE SOVIET UNION:
ZIL'BERMAN, ET AL, SOVIET PHYSICIST JETP 15, 100 (1972)

1977:

- FIRST WORK IN U.S. REPORTED IN 1977:
MELLMAN, J. IPT. SOC. AMER., 63, 1987

1982-83:

- WORKING FROM RESULTS IN 1 JAPANESE, PHASE-LOCKED LASER
DEMO IN LAB

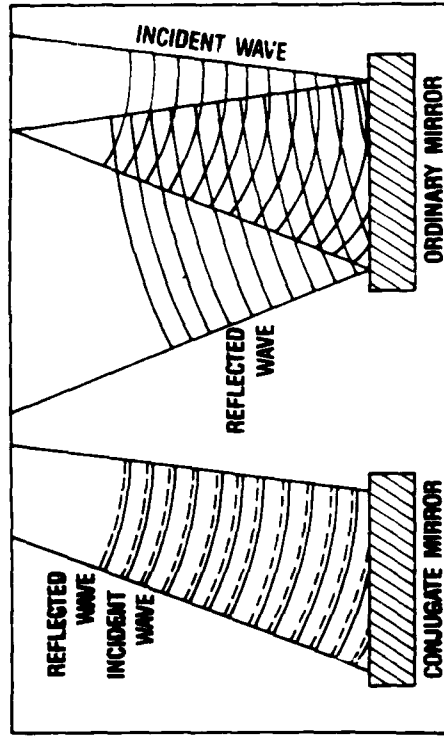
1983-84:

- FIRST COMMERCIAL PHASE COHERENCE EXPERIMENTS WITH
RESULTING PATENT APPLICATIONS

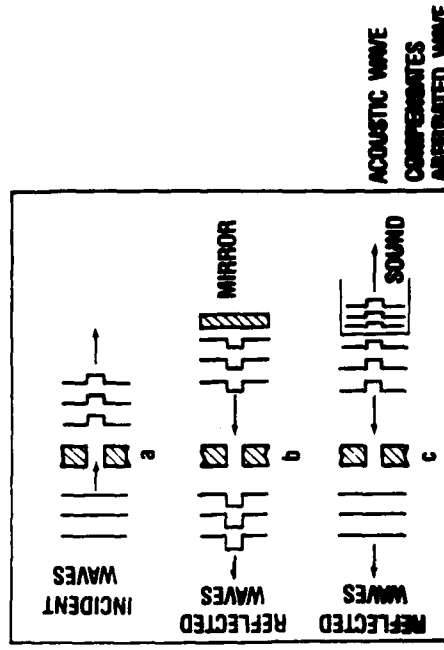


PRINCIPLES OF OPTICAL PHASE CONJUGATION

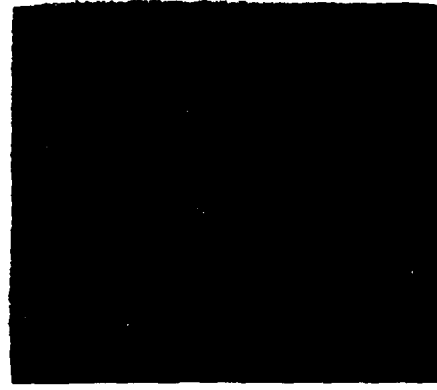
ANGULAR COMPENSATION



ABERRATION COMPENSATION



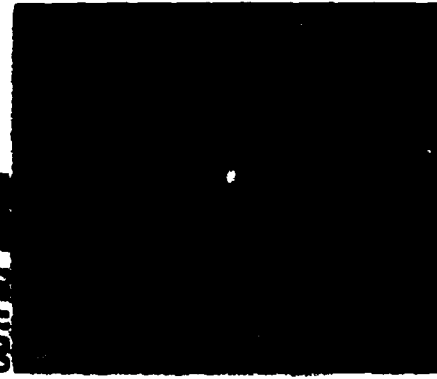
ORIGINAL BEAM



DISTORTED OUTPUT

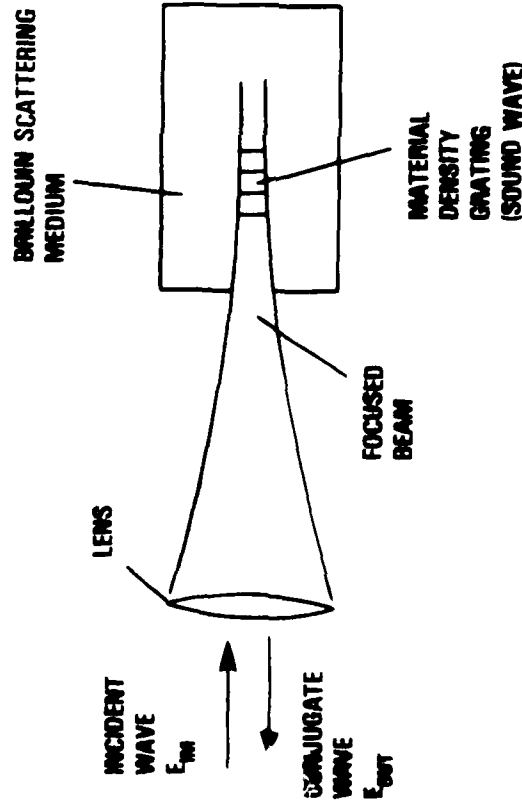


PHASE-CONJUGATED
OUTPUT BEAM





PHASE CONJUGATION IMPLEMENTATION VIA STIMULATED BRILLOUIN SCATTERING



SBS MEDIA SUMMARY:

ACETONE LIQUID

CARBON DISULFIDE LIQUID

METHANE GAS AT 150 ATM

CARBON TETRACHLORIDE LIQUID

BENZENE LIQUID

NITROGEN GAS AT 300 ATM

~~CYCLOHEXENE~~ LIQUID

WATER

QUARTZ CRYSTAL

SBS PHYSICS: ELECTROSTRICTIVE EFFECT:

DENSITY VARIATIONS $\sim$ ELECTRIC FIELD

RESULT: FORMATION OF DENSITY GRATING (ACOUSTIC WAVE)

UNCLASSIFIED

WANTS AND REQUIREMENTS

● **WANT:**

MORE ENERGY, POWER, BRIGHTNESS.

LESS WEIGHT, ENERGY CONSUMPTION.

● **THIS REQUIRES:**

GREATER LASER EFFICIENCY

UNCLASSIFIED



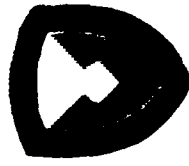
PHASE CONJUGATION IMPACT UPON RELIABILITY AND PRODUCIBILITY

- **ELIMINATES BEAM WANDER/REDUCES DEMANDS ON
BEAM POINTING**
- **SIGNIFICANT WEIGHT REDUCTION (30%) WITH
INCREASED STABILITY**
- **INCREASED OVERALL EFFICIENCY (1.5-2%)**
- **ALLOWS USE OF LOWER QUALITY, YAG RODS/COST
SAVING**
- **REDUCED PRODUCTION COSTS DUE TO INHERENT
ALIGNMENT ($\ll$ LABOR)**
- **SCALABLE TO JOULE/KILOJOULE LEVEL**

PHASE CONJUGATE MIRROR

HUGHES

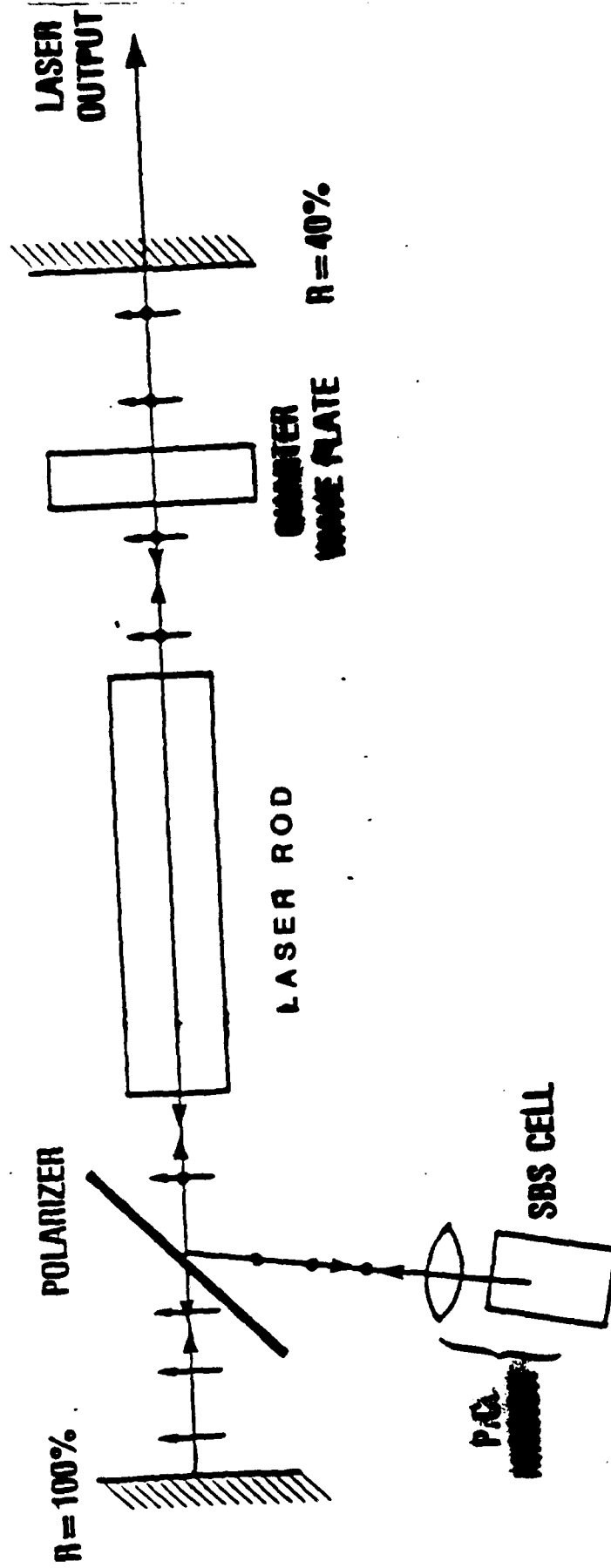




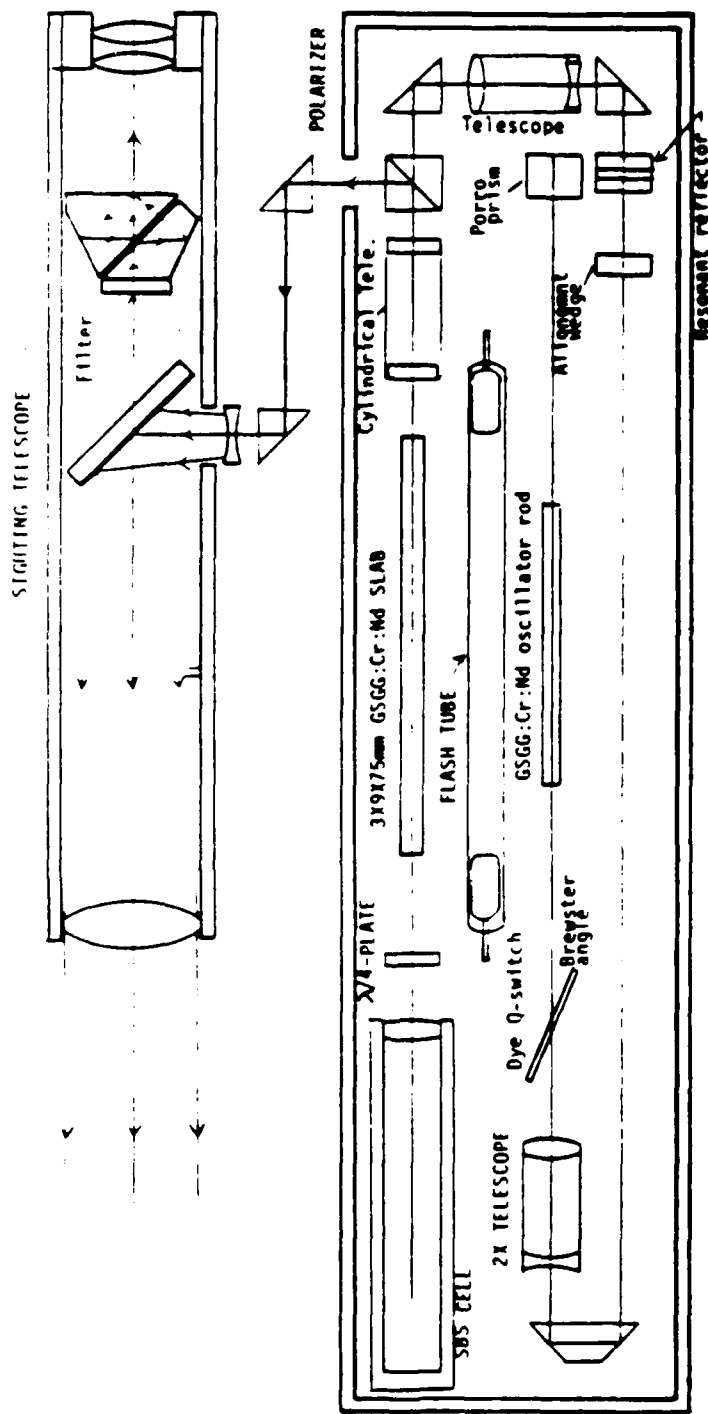
NVEOC PHASE CONJUGATION PATENTS

- 1. "SIDE ARM PHASE CONJUGATED LASER," #779,762**
- 2. "PHASE CONJUGATED SLAB LASER DESIGNATOR"**
- 3. "PHASE CONJUGATED HYBRID SLAB LASER"**
- 4. "PHASE CONJUGATED FULL APERTURE FOUR PASS LASER AMPLIFIER"**

PROPOSED Q-SWITCH LASER APPARATUS



PHASE CONJUGATED SLAB LASER DESIGNATOR



FULL APERTURE FOUR-PASS DESIGN

- BETTER ENERGY EXTRACTION
- POSSIBLE ONLY WITH STRAIGHT-THROUGH SLABS

4/10/00

UNCLASSIFIED

CONSEQUENCE OF THERMAL EFFECTS

- BEAM DEGRADATION DUE TO

- (A) BIREFRINGENCE

- (B) WAVEFRONT DISTORTIONS

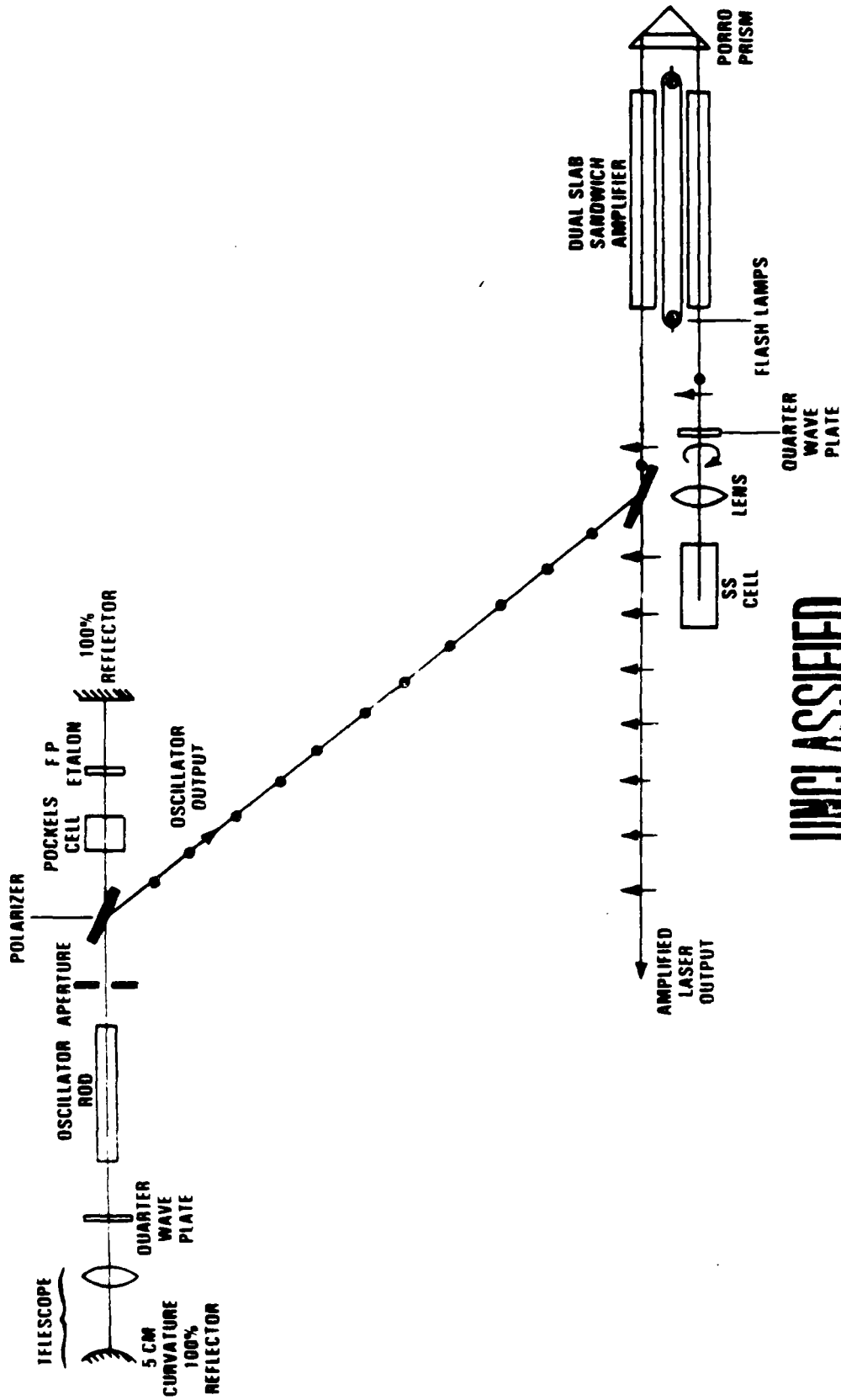
- BEAM POINTING ERRORS

UNCLASSIFIED

DESIGN APPROACH

- **OSCILLATOR-AMPLIFIER**
- **SLAB**
- **PHASE CONJUGATION**
- **SANDWICH PUMPING DESIGN**
- **FULL APERTURE FOUR-BEAM PASSES**

UNCLASSIFIED

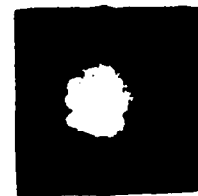


UNCLASSIFIED

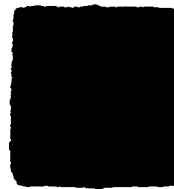
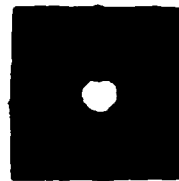
UNCLASSIFIED

MIRROR VS. PC REFLECTED AMPLIFICATION

MIRROR
REFLECTION



PC
REFLECTION



PRF →

UNCLASSIFIED

PHASE CONJUGATION WORKSHOP

TECHNICAL ISSUES

- **COMPETING PROCESSES**
- **SCALING ISSUES (CONFIGURATION)**
- **ALTERNATIVE MEDIA (GLASSES)**
- **FIDELITY**

CNVEO & U of R

5. LIST OF ATTENDEES

Electro-Optic Workshop

22 March 1988

Dr. Rohde	CNVEO
L.N. Durrasula	CNVEO
Robert Boyd	Univ of Roch
Suresh Chandra	CNVEO
John Pollard	CNVEO
Mark Norton	CNVEO
James Habersat	CNVEO
Tom Stone	Univ of Roch
Ken MacDonald	Univ of Roch
Nicholas George	Univ of Roch
Rich Utano	CNVEO
Wayne Movis	CNVEO
Dr. Buser	CNVEO
Susan St. Cyr	Polaroid

END

DATE

FILMED

DTIC

9-88