AFRL-ML-WP-TP-2007-523

SELF-PUMPED PHOTOREFRACTIVE GRATINGS IN $Fe:KNbO_3$ (PREPRINT)

Dean R. Evans, G. Gook, J.L. Carns, and M.A. Saleh

Hardened Materials Branch
Survivability and Sensor Materials Division

JANUARY 2006

Approved for public release; distribution unlimited.
See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-ML-WP-TP-2007-523 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

DEAN R. EVANS, Ph.D.
Agile Filters Project
Exploratory Development
Hardened Materials Branch

//Signature//

MARK S. FORTE, Acting Chief
Hardened Materials Branch
Survivability and Sensor Materials Division

//Signature//

TIM J. SCHUMACHER, Chief
Survivability and Sensor Materials Division

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
January 2006

2. REPORT TYPE
Conference Paper Preprint

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
SELF-PUMPED PHOTOREFRACTIVE GRATINGS IN $Fe:KNbO_3$ (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
Dean R. Evans (AFRL/MLPJ)
G. Cook (Universal Technology Corporation)
M.A. Saleh (UES, Inc.)
J.L. Carns (General Dynamics Information Technology, Inc.)

5d. PROJECT NUMBER
4348

5e. TASK NUMBER
RG

5f. WORK UNIT NUMBER
M08R1000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Hardened Materials Branch (AFRL/MLPJ)
Survivability and Sensor Materials Division
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

Universal Technology Corporation
1270 North Fairfield Road
Dayton, OH 45432

UES, Inc.
Dayton, OH 45432

General Dynamics Information Technology, Inc.
5100 Springfield Pike, Suite 509
Dayton, OH 45431

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-ML-WP-TP-2007-523

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/MLPJ

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2007-523

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference slideshow submitted to the Proceedings of the Third International Photorefractive Workshop.

The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. PAO Case Number: AFRL/WS 06-0322, 07 Feb 2006.

14. ABSTRACT

- High gain confirmed in off-axis geometries for $Fe:KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane
- Large apparent variation in the effective trap density with crystal angle
- Modified theory gives a good fit to experimental data
- Mechanism for trap density anisotropy is unclear

15. SUBJECT TERMS
Photorefractive, Potassium Niobate, Two-Beam Coupling, Focal Plane

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	SAR	20	Dean R. Evans
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Self-Pumped Photorefractive Reflection Gratings in $Fe:KNbO_3$

G. Cook[a,b], J. L. Carns[c],
M. A. Saleh[d], D. R. Evans[a]
[a]Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH
[b] Universal Technology Corporation, Dayton, OH
[c]Anteon Corporation, Dayton, OH
[d]UES, Dayton, OH

Outline

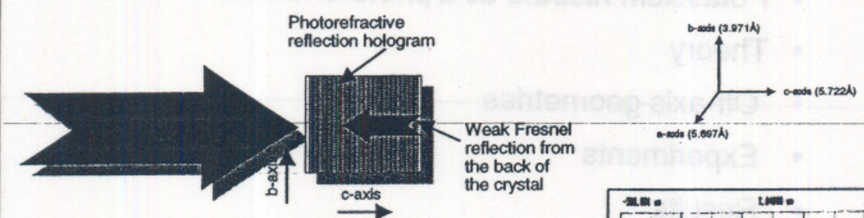
- Potassium niobate as a photorefractive
- Theory
- Off-axis geometries
- Experiments
- Results
- A controversial suggestion……
- Discussion
- Conclusion (confusion?)

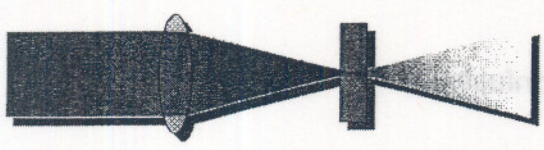
Potassium niobate as a photorefractive

- High trap density
  - Allows efficient counter-propagating gratings to be written
- High sensitivity
  - Fast response times
- Broad spectral response
  - 400nm - ~700nm (with Fe doping)
  - 400nm - >700nm? (with Ni doping)
- Difficult to grow reproducibly
  - Program under way to fix this (looks very promising!)

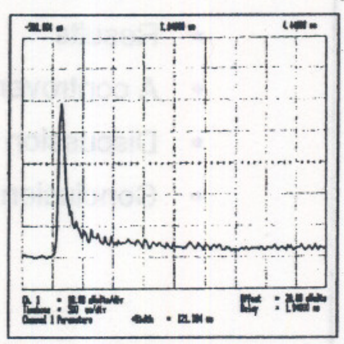
Experiment

- Self-pumped two beam coupling





Focal plane geometry



Theory

- Optical fields

$$E_s(z,t)=\frac{1}{2}A_s(z,t)\exp i(-kz-\omega t)+c.c$$
$$E_p(z,t)=\frac{1}{2}A_p(z,t)\exp i(+kz-\omega t)+c.c$$

- Intensity fringes

$$I(z,t)=\left(I_s+I_p\right)\left(1+\frac{A_sA_p^*}{I_s+I_p}\exp(2ikz)+c.c.\right)$$

$$\frac{dN_d^+}{dt}=s\left(I+I_{Dark}\right)\left(N_d-N_d^+\right)-\gamma_r nN_d^+$$
$$\frac{dn}{dt}=\frac{dN_d^+}{dt}+\frac{1}{e}\frac{dJ}{dz}$$
$$J=e\mu nE_{sc}+\mu k_BT\frac{dn}{dz}+sI\left(N_d-N_d^+\right)e\delta$$
$$\varepsilon_s\frac{dE_{sc}}{dz}=e\left(N_d^+-N_a^--n\right)$$

(Kiev group/Kukhtarev material equations)

$A_{s,p}$ are the slowly varying amplitudes of the electric fields

Theory

- Solving the Kiev group/Kukhtarev's equations for the space charge field gives:

$$\frac{a}{\tau_{di}}\frac{\partial E_{sc}}{\partial t}+bE_{sc}+cm=0$$

- Where:

$$m=\frac{\sqrt{I_sI_p}}{I_s+I_p+I_{Erasure}}\exp(-i\varphi),$$
$$a=1+\frac{E_d}{E_m}-i\frac{E_0}{E_m},$$
$$b=1+\frac{E_d}{E_q}-i\left(\frac{E_0+(N_a/N_d)E_{pv}}{E_q}\right),$$
$$c=E_0+E_{pv}+iE_d$$
$$\tau_{di}=\varepsilon_s\gamma_rN_a/e\mu s(I_p+I_s+I_{Erasure})(N_d-N_a)$$
$$E_d=\frac{2\pi k_BT}{e\Lambda}$$
$$E_q=(1-N_a/N_d)\,eN_a/2k\varepsilon_s$$
$$E_{pv}=\gamma_rN_a^-\delta/\mu$$
$$E_m=\gamma_rN_a/(\mu K)$$

Theory

- The space charge field modifies the refractive index through the linear Pockels effect
- Substituting the modulated index into the optical wave equation gives the coupled equations for the intensities and phase:

$$\frac{\partial I_p}{\partial z} = -\alpha I_p - \frac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right)$$

$$\frac{\partial I_s}{\partial z} = +\alpha I_s - \frac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right)$$

$$\frac{\partial \varphi}{\partial z} = \frac{\pi n^3 r_{eff}(I_p - I_s)}{\lambda\sqrt{I_p I_s}}\mathrm{Re}\left(E_{sc}\exp(i\varphi)\right)$$

Theory

- In steady state the space charge field and coupled equations reduce to:

$$E_{sc}(z) = \frac{-\left(E_0 + iE_d + E_{pv}\right)m(z)}{1 + \frac{E_d}{E_q} - i\left(\frac{E_0}{E_q} + \frac{N_a E_{pv}}{N_d E_q}\right)}$$

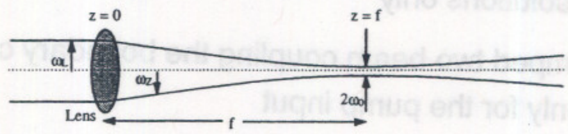
$$\frac{dI_p}{dz} = -\alpha I_p - \Gamma\frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

$$\frac{dI_s}{dz} = +\alpha I_s - \Gamma\frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

Where $\Gamma = \frac{2\pi}{\lambda} n^3 r_{eff}\,\mathrm{Im}(E_s)$

Theory

- Focusing



$$\frac{dI_p}{dx} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f) I_p}{z_R^2 + (z-f)^2}$$

$$\frac{dI_s}{dx} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f) I_s}{z_R^2 + (z-f)^2}$$

Theory

- Piezoelectric/photoelastic contributions[1,2]

$$r_{ij}^{eff} = r_{ijk}^{S} \hat{n}_k + p_{ijkl}^{'E} \hat{n}_l A_{km}^{-1} B_m$$

$$A_{ik} = C_{ijkl}^{E} \hat{n}_j \hat{n}_l$$

$$B_i = e_{kij} \hat{n}_k \hat{n}_j$$

r_{ijk}^{S} is the clamped EO tensor

$p_{ijkl}^{'E}$ is the effective elasto-optic tensor

C_{ijkl}^{E} is the elastic stiffness tensor

e_{kij} is the piezoelectric tensor

- Scalar effective EO coefficient:

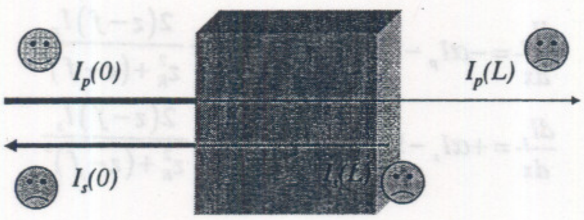
$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

1) M. Zgonik, K. Nakagawa, P. Günter, "Electro-optic and dielectric properties of photorefractive BaTiO3 and KNbO3", J. Optical Society of America B, vol. 12, no. 8, pp 1416-1421, 1995.

2) M. Zgonik, R. Schlesser, I. Biaggio, E. Voit, J. Tscherry, P. Günter, "Materials constants of KNbO3 relevant for electro- and acousto-optics", J. Applied Physics, vol. 74, no. 2, pp 1287-1297, 1993.

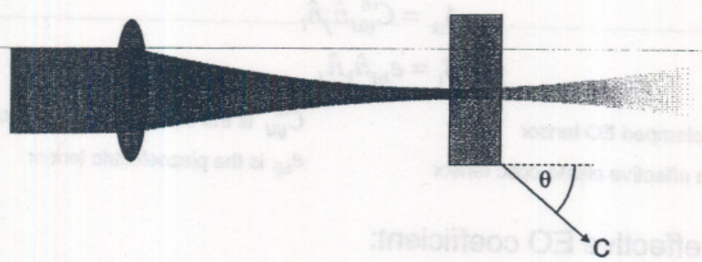
Theory

- No closed form solution to the coupled equations
- Numerical solutions only
- For self pumped two beam coupling the boundary conditions are known only for the pump input
- Iterative shoot and match methods are required



Off-axis concept

- Optical gain is potentially much higher away from the c-axis

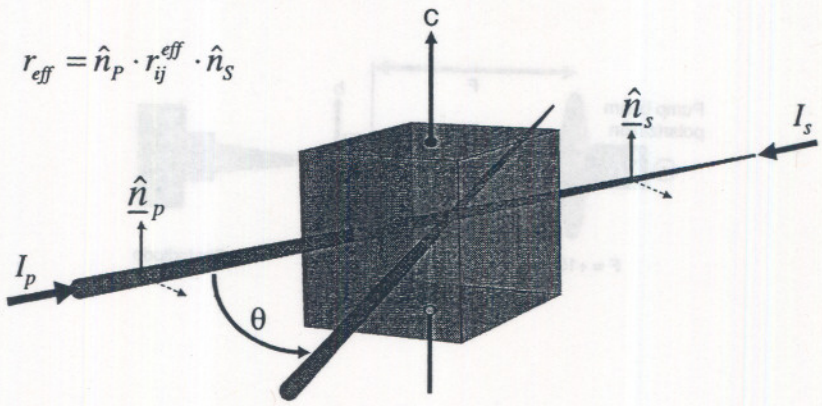


- c-axis is best for $Fe:LiNbO_3$ owing to the huge PV effect
- The same is NOT true for $Fe:KNbO_3$

Off-axis effective electro-optic coefficient

- Beam axis rotation about the c-axis:

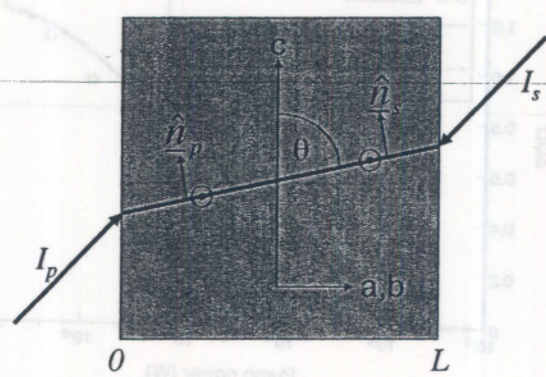
$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$



r_{eff} is <u>zero</u> for all polarizations

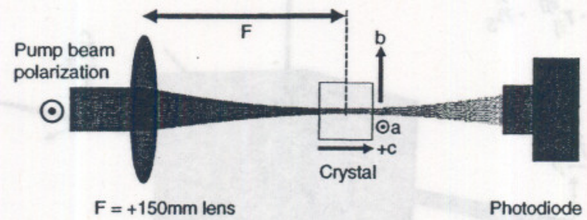
Off-axis effective electro-optic coefficient

- Beam axis rotation in the a-c or b-c planes:

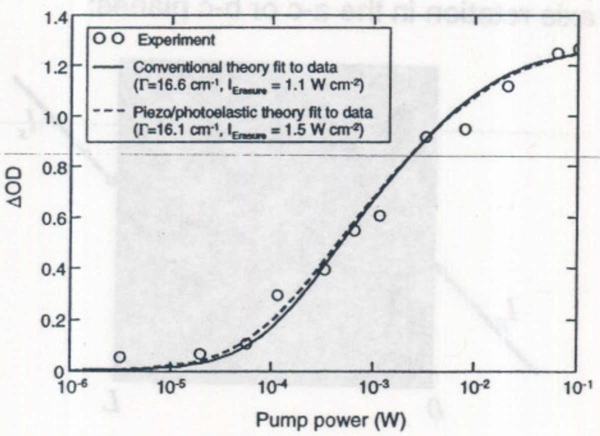


$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

Determination of Γ and $I_{Erasure}$



Determination of Γ and $I_{Erasure}$

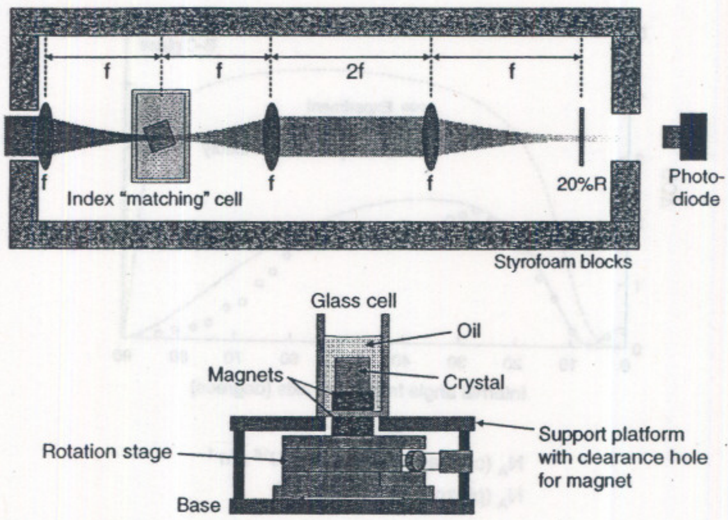


N_A (conventional) = 2.1×10^{16} cm^{-3}

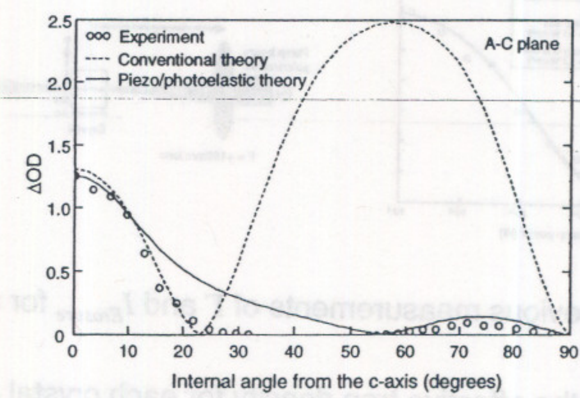
N_A (piezo) = 5.0×10^{16} cm^{-3}

Measuring the off-axis gain in contra-directional $Fe:KNbO_3$

- Experiment:



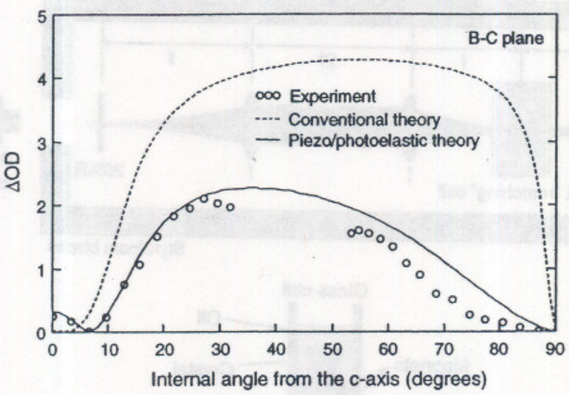
Off-axis gain results



N_A (conventional) = 2.1×10^{16} cm^{-1}

N_A (piezo) = 5.0×10^{16} cm^{-1}

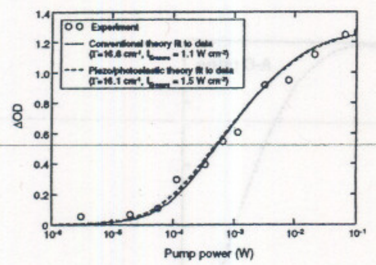
Off-axis gain results

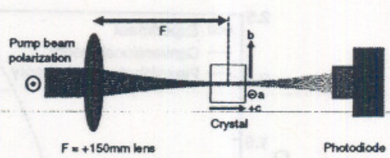


N_A (conventional) = 2.1×10^{16} cm^{-1}

N_A (piezo) = 5.0×10^{16} cm^{-1}

A controversial suggestion....

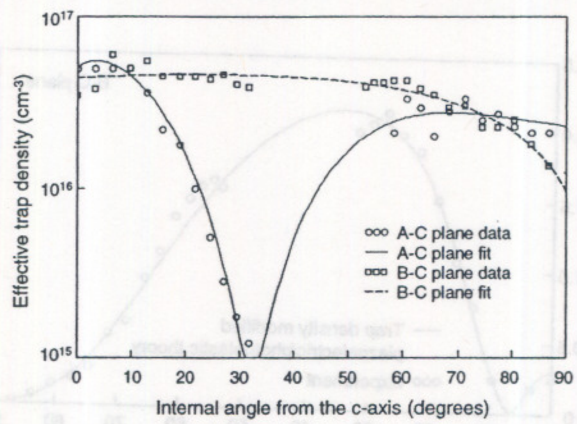




- Repeat previous measurements of Γ and $I_{Erasure}$ for all crystal angles
- Calculate the effective trap density for each crystal angle

"Conventional" transmission/reflection grating method cannot be used reliably for trap density measurements owing to admittance angular restrictions at large crystal angles and competition from rear Fresnel reflection.

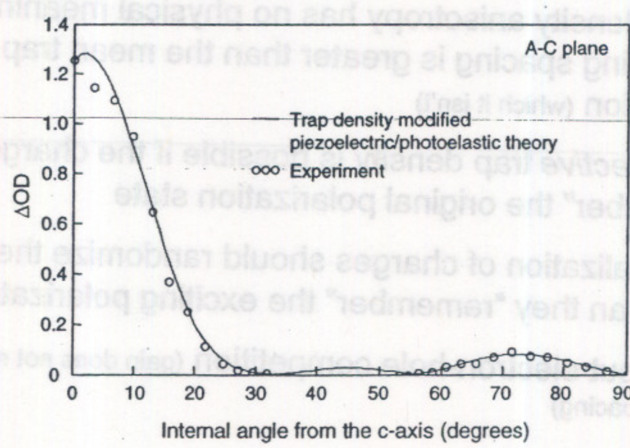
Effective trap density variations?



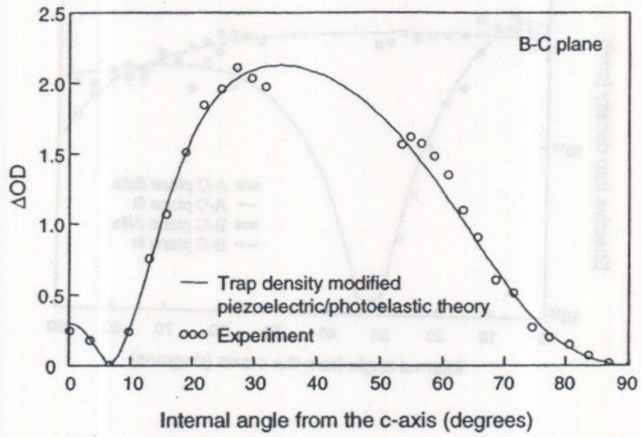
$$N_{A(AC)} = -9.09\times10^{12}\theta^6 + 3.03\times10^{15}\theta^5 - 3.85\times10^{17}\theta^4 + 2.26\times10^{19}\theta^3 - 5.67\times10^{20}\theta^2 + 3.21\times10^{21}\theta + 5\times10^{22}$$

$$N_{A(BC)} = -6\times10^{16}\theta^3 + 1\times10^{20}\theta + 4.42\times10^{22}$$

Theory modified for apparent trap density variations



Theory modified for apparent trap density variations



Discussion

- Trap density anisotropy has no physical meaning unless the grating spacing is greater than the mean trap separation (which it isn't)
- An *effective* trap density is possible if the charges "remember" the original polarization state
- Delocalization of charges should randomize the charge state (can they "remember" the exciting polarization?)
- Rule out electron-hole competition (gain does not reverse with grating spacing)

Summary

- High gain confirmed in off-axis geometries for $Fe:KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane
- Large apparent variation in the effective trap density with crystal angle
- Modified theory gives a good fit to experimental data
- Mechanism for trap density anisotropy is unclear