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INVESTIGATION OF THE SELF-PUMPED TWO-BEAM COUPLING IN A PHOTOREFRACTIVE MATERIAL USING BEAM PROPAGATION SIMULATION (Preprint)

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Hardened Materials Branch
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14. ABSTRACT

- At this point we are capable of stimulating the self-pumped contra-directional two-beam coupling in a photorefractive medium with arbitrary shaped beams.
- Our simulation shows positive role of the photovoltaic effect in self-pumped contra-directional TBC, in agreement with experimental observation.

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Investigation of the self-pumped two-beam coupling in a photorefractive material using beam propagation simulation

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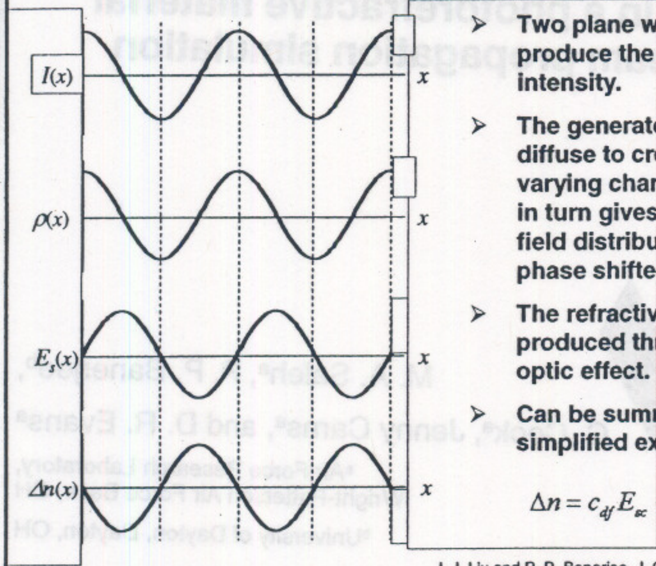
Outline

- Photorefractive two-beam coupling
- Motivation of this work
- Beam propagation method
- Simulation results
- Conclusions

Diffusion Model of Photorefraction

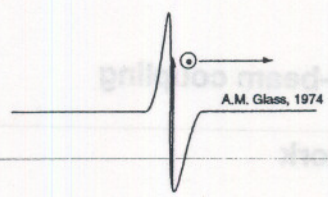


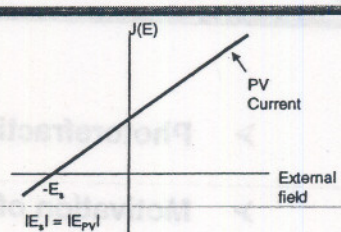
- Two plane waves interfere to produce the spatially modulated intensity.
- The generated free charge carriers diffuse to create the spatially varying charge distribution, which, in turn gives rise to a electrostatic field distribution that is 90-degree phase shifted.
- The refractive index variation is produced through the linear electro-optic effect.
- Can be summarized by this simplified expression[1]

$$\Delta n = c_{df} E_{sc} \propto \nabla I(x, y, z)$$

J. J. Liu and P. P. Banerjee, J. Opt. Soc. Am. B. 11, pp. 1688-1693, 1994

Photovoltaic Effect



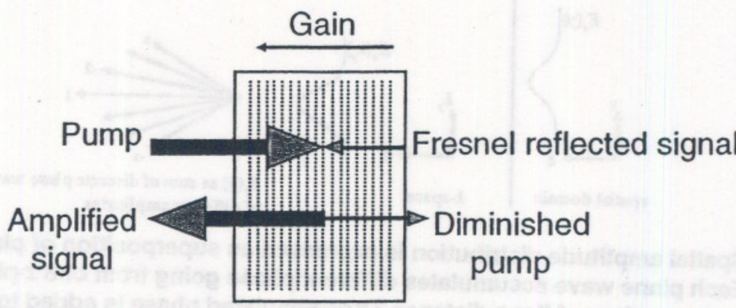


- In addition to the diffusion process, some anisotropic crystals (i.e., $LiNbO_3$) exhibit strong photovoltaic effect which refers to the tendency of the photo-ionization process (under uniform illumination) to eject the electron in a preferred direction due to the asymmetric potential in the anisotropic crystal.

$$\Delta n = c_{PV} E_{sc} \propto I(x, y, z)$$

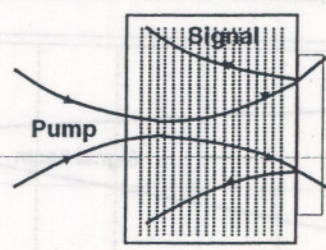
- Resulting current flow can be opposed by applying an external E-field.
- In the closed circuit condition the photocurrent will equal zero at $-E_S$, the effects of the PV and ext. E-field cancel out.
- Under open circuit condition it is generally assumed that the bulk field cancels out the photovoltaic field and PV effect does not assist TBC.

Contra-directional Self-pumped Two-beam coupling



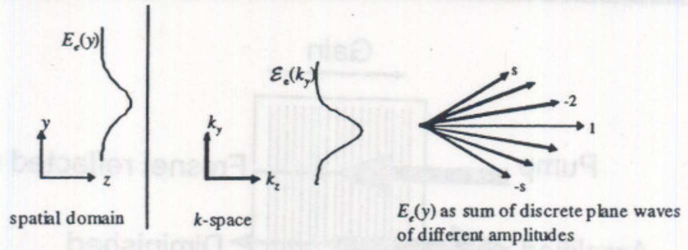
Periodic index modulation from the photorefractive effect can be used to couple energy between two interfering beams. One novel variation of the contra-directional beam coupling is the self-pumped beam-coupling where the signal beam is generated by the Fresnel reflection of the pump.

Motivation and goals

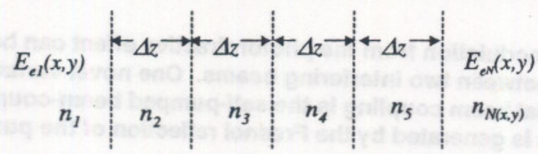


- **Strong dependence of the TBC efficiency on the spot size is observed, attributed to diffraction and the resulting change in the spatial overlaps.**
- **The goal of our simulation:**
  - **is to simulate arbitrary shaped beam-coupling using exact diffraction.**
  - **is to analyze the contribution from photovoltaic effect and diffusion in two-beam coupling.**
- **To the best of our knowledge, self-pumped contra-directional TBC has not been done with BPM.**

Split-step Beam Propagation

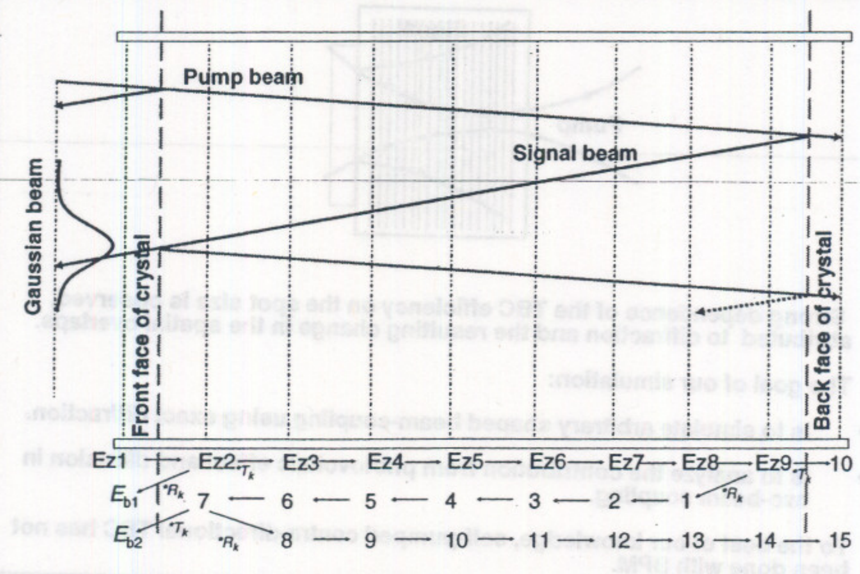


Spatial amplitude distribution is expressed as superposition of plane waves. Each plane wave accumulates different phase going from one *z*-plane to anther *z*-plane. After a distance Δz accumulated phase is added to each plane wave and the spatial amplitude distribution can be recalculated again.

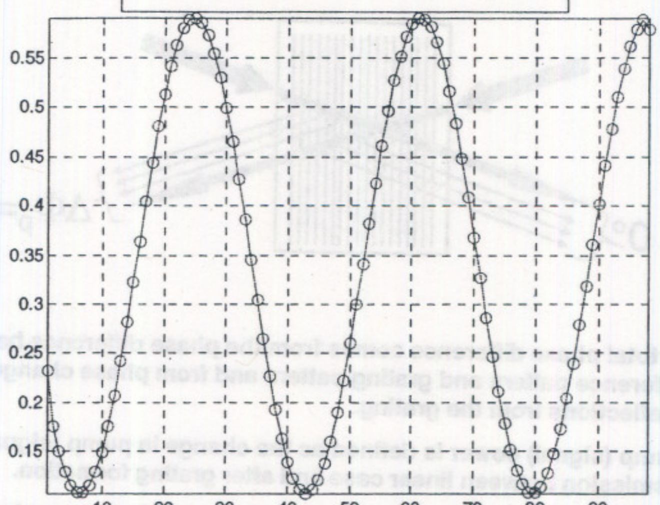


The optical path is broken into a sequence of finite steps.

Schematic



Simulated Interference



Steps of simulation

- We simulate the interference of the beams by adding the forward and backward propagating beams at every incremental z value. This produces the modulated $I(z)$ inside the crystal.
- We use this modulated intensity to calculate the space charge field. Change in index then can be calculated from the electro-optic effect.
- We modify the index inside the crystal by using the simplified expression[1] (omitting the details of space charge field generation):

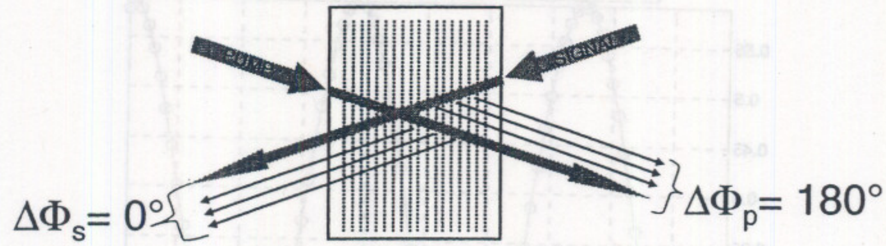
$$n = n_0 + \Delta n, \quad \text{where } \Delta n = c_{PV} E_{sc} \propto I(x,y,z) \quad \text{(PV)}$$

$$\text{or, } \Delta n = c_{df} E_{sc} \propto \nabla I(x,y,z) \quad \text{(diffusion)}$$

- For this work only a λ long crystal was simulated. We chose the two constants such that there was observable beam coupling in this thin crystal and the Δn is same for both diffusion and PV effect.

J. J. Liu and P. P. Banerjee, *J. Opt. Soc. Am. B.* **11**, pp. 1688-1693, 1994[1].

Condition for Beam coupling

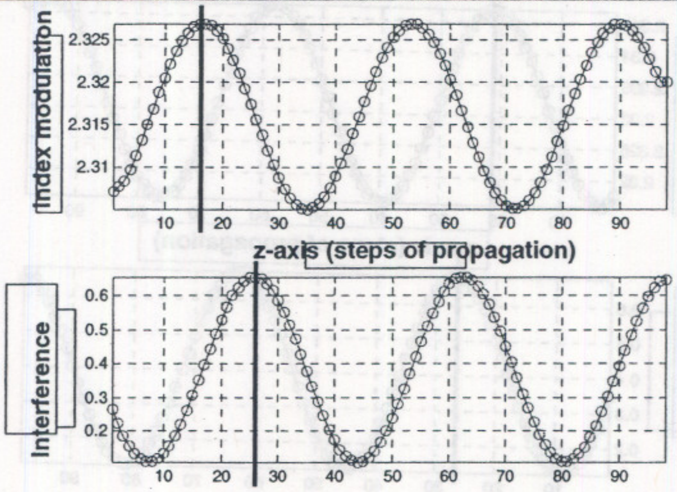


- This total phase difference comes from the phase difference between interference pattern and grating pattern and from phase change due to the reflections from the grating.
- Δ pump (signal) power is defined as the change in pump (signal) transmission between linear case and after grating formation.
- Δ pump power and Δ signal power tells if destructive or constructive interference has taken place.

Steps of convergence

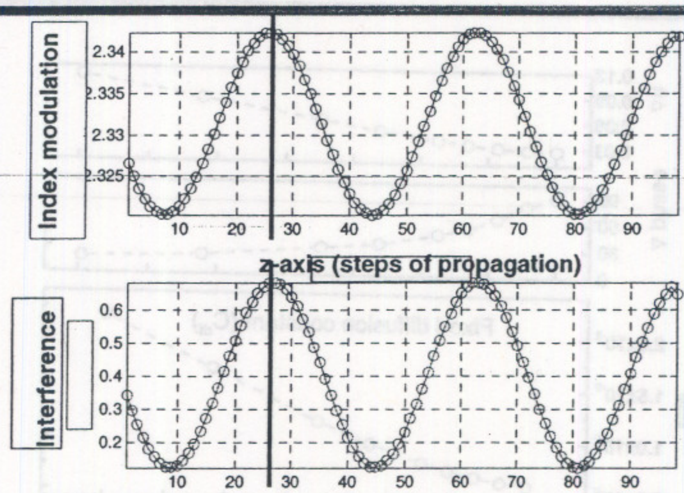
- For a given intensity distribution $I(x,y,z)$ inside the crystal, we calculate $n(x,y,z)$.
- We obtain a new intensity distribution $I(x,y,z)$ through another round of beam propagation, where pump and signal scatters are also accounted for, which gives us a new $n(x,y,z)$.
- Error is defined as the average percent difference between successive interference amplitude arrays.
- We continue the process until we obtain a converged steady state solution for both $I(x,y,z)$ and $n(x,y,z)$ using iterative shooting method.
- For the converged $I(x,y,z)$ and $n(x,y,z)$ pump and signal scatters are added to signal and pump respectively and the power changes due to the interference are calculated.

Considering diffusion alone



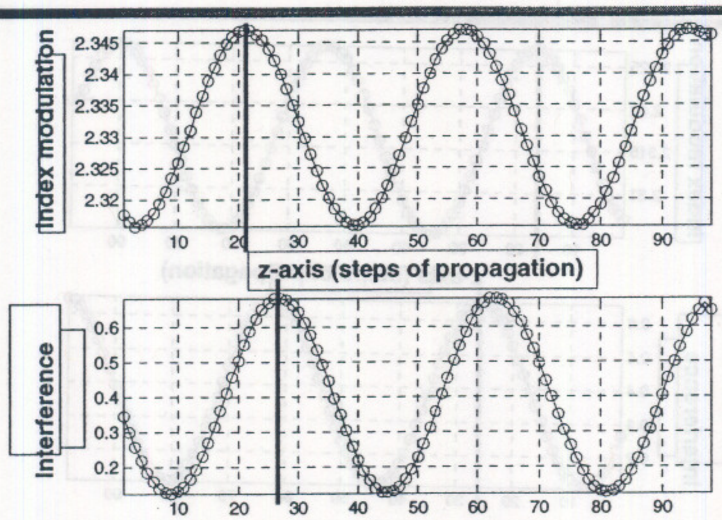
The index and interference are 90-degree out of phase (as expected). Δn = 0.022 (for C_{df} = 0.27). ΔP = 0.58 % of pump power. C_{df} = -0.27 (equivalent to rotating optic axis 180°) makes ΔP = -0.58 % of pump power.

Considering PV alone



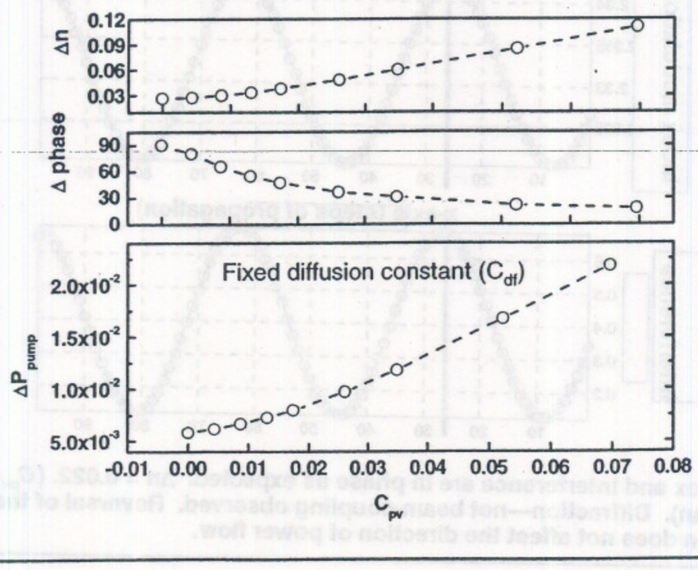
The index and interference are in phase as expected. Δn = 0.022. (C_{pv} Chosen to match Δn). Diffraction—not beam-coupling observed. Reversal of the crystal direction does not affect the direction of power flow.

Considering both PV and Diffusion

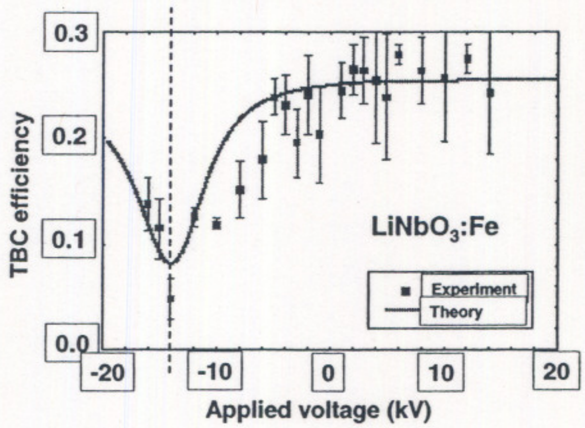


Phase difference > 0 and < 90 deg. Δn = 0.031, larger than considering them alone. ΔP changes with PV contribution.

Photovoltaic Contribution



Observed photovoltaic contribution



G. Cook, J. P. Duignan, D. C. Jones, "Photovoltaic contribution to counter-propagating two-beam coupling in photorefractive lithium niobate" Optics communications, vol. 192, pp 393-398, 2001.

$$E_s = \frac{E_0 + iE_D + E_{PV}}{1 + E_D / E_Q - i(E_0 / E_Q + (N_A / N_D)(E_{PV} / E_Q))}$$

Conclusions and Future Work

- At this point we are capable of simulating the self pumped contra-directional two-beam coupling in a photorefractive medium with arbitrary shaped beams.
- Our simulation shows positive role of the photovoltaic effect in self-pumped contra-directional TBC, in agreement with experimental observation.
- A more complete simulation that includes dark conductivity and un-simplified space charge field is in progress.