# Rapport

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## Abstract

By Jesper Graungaard Bertelsen

It’s 2025 and today we use photonics in collaboration with electronics. It sets the speeds in terms of the slowest part, electronics, but also requires power when transferring between the two.   
Increasingly more data is being used but we’re about to reach the limit of maximization with electronics. Transferring over to using photonics from end to end, it might have the potential to decrease energy consumption, fastening the speeds while also being able to work in parallel due to multiplexing of light. But when searching for photonic storage online, nothing really comes to scope. Holographic storage seems to be the possibility for photonic storage, and it has been worked on in the last couple of decades, and it’s becoming better and better. Using crystals to store interference patterns one can write, read and erase contents of the crystal. For my design study I will try to discover, what a crystal suitable for high-speed holographic data storage is and then find out if any other crystals typically not used could be suitable candidates as well.  
I will be taking the article “Matching for realizing high-speed reading in holographic data storage system” as reference, and I’ll be testing crystal properties using softwares such as Emode photonics.

## References

Matching for realizing high-speed reading in holographic data storage system ( 2024 ), Jing Xu, Yongkun Lin, Linli Zhong, Yuping Ke, Chen He, Sheng Lin, Dakui Lin, Xiao Lin and Xiaodi Tan,   
<https://opg.optica.org/oe/fulltext.cfm?uri=oe-32-26-46259&id=565113>

*Similar tests made previously:* A precision tester for studies of holographic optical storage materials and recording physics ( 1996 ), M.-P. Bernal, H. Coufal, R. K. Grygier, J. A. Hoffnagle, C. M. Jefferson, R. M. Macfarlane, R. M. Shelby, G. T. Sincerbox, P. Wimmer, and G. Wittmann  
<https://opg.optica.org/ao/abstract.cfm?uri=ao-35-14-2360&origin=search>

## Hvad jeg har fokus på

Det ville være en god idé at snævre mit arbejde lidt ned. Derfor har jeg plukket bare 3 af en krystals egenskaber som jeg synes kunne være spændende at se på.

### Response tid

Taler for sig selv. Mit abstract tager udgangspunkt i at krystallerne skal bruges til highspeed storage. Derfor vil response tiden, for hvor langt tid en krystal tager om at blive skrevet eller læst, være vigtigt.

### Saturation intensity

Den lyder også meget relevant. Tanken bag mit design study er at blive klogere indenfor om fotonik fra ende til ende vil kunne være med til at give fordele i hastighed, kapacitet og energi. Særligt den sidste del er gældende her, da saturation intensity beskriver hvor meget intensitet laseren skal bruge for at læse eller skrive i krystallerne. Meget relevant indenfor energi forbrug.

### Diffraction effiency

Hvor stor en procentdel det rekonstruerede signal har i intensitet sammenlignet med intensiteten for det originale signal.

Chatten siger at der er et approksimativ forhold på

### Til næste gang

Jeg har fået set på nogle egenskaber for GaAs og LiNbO3 og har fået et bedre overblik over, hvad der gør dem specielle. Jeg har ledt i videnskabelige artikler efter information, men har ikke givet et kig i datablade et forsøg endnu. Måske er informationen allerede let tilgængelig?  
Mit grove estimat på en relation mellem response tid og en krystals materiale egenskaber vil måske kunne være nyttigt, når jeg skal til at se på mere ”Ukendte” materialer.

Måske se på BSO og BGO også som de velkendte krystaller og så er det det for dem.

Og så begynde at tænke i tankerne, hvad jeg ønsker at simulere.

Tænke over hvordan jeg kan bruge diffraction efficiency til at teste modes.   
Chatten nævnte noget med diffraction efficiency mod refraktion index modulation. Det og hvordan sammenhængen mellem de to er, er til sidst i dokumentet.

Spørgsmål

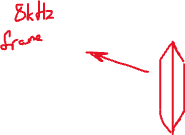
Okay, let's say these interference patterns are purely periodic. How do I relate that into terms of diffraction efficiency?

## Undersøgelse.

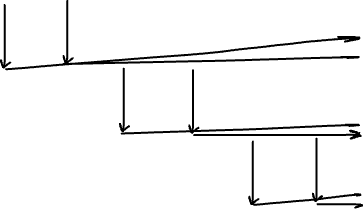
Matching af hastigheder:   
Det ser ikke ud til, at det er kameraets indstilling der begrænser læse hastigheden.  
Chatten forklare også, at der ikke er krystallen direkte, der begrænser systemet. Den er en del af det electric displacement table with Media, men hvis krystallen ikke har de rigtige egenskaber, så kunne det potentielt være en bottleneck.

Et billede, der indeholder tekst, diagram, linje/række, Font/skrifttype

Automatisk genereret beskrivelse



Reading frame rate 8kHz -> 5.8 GB/s -> 1280\*(550 - 600ish) \* 8000’’’  
8000 “Hologrammer pr. sekund, det kan være forskellige krystaller eller forskellige interferens mønstre i krystallerne.



## Eksempel fra en MIT snak

<https://www.youtube.com/watch?v=kMoUlAiPSdo&t=186s>

3000cd/m^2

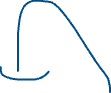
1/4 mm resolution.

300mm x 300mm skrevet på 8 sekunder.

300mm x 300mm svarer derfor til en resolution på 1200x1200 pixels.

Som jo egentlig er ingenting i forhold til, resultatet i artiklen, men det her var også i 2012.Et billede, der indeholder tekst, diagram, skærmbillede, design

Automatisk genereret beskrivelse



## Hvad jeg har haft sluttet på:

Photorefractive response  
Måske kan man finde response tiden for GaAs i den her artikel. Men jeg kan ikke få adgang tid optica hjemmefra.   
<https://opg.optica.org/viewmedia.cfm?r=1&rwjcode=ol&uri=ol-19-21-1702&html=true>

Eller noget information på LiNbO3 her:

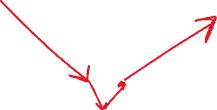
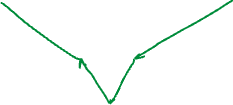
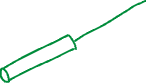
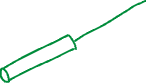
<https://pubs.aip.org/aip/apl/article/126/1/011904/3329185/Enhanced-red-light-photorefractive-response-speed>

” Notably, the … crystal significantly improved PR response speed at 671 nm, with a response time of 1.67 s, nearly three times shorter than that of ⁠…”

### Diffraction efficiency

**Simple relationship:**For thin gratings (first approximation),  
   
(meaning diffraction efficiency increases with the square of the refractive index modulation.)

Grunden til det også har indflydelse på hastigheden er, at fordi intensiteten af det rekonstruerede signal er lavt ved en lav diffraction efficiency, så vil man skulle efter processere det for at få et signal som man ville kunne bruge, f.eks integrere over de svage signaler.   
  
Data-skrivning/læsning  
To laseres photoner går sammen i en krystal og laver interferens. Interferensen medføre en midlertidig skift i krystallens reflektionsindeks ved de lyse frynser som gør at informationen er gemt.



Så hvad der bidrager til diffraction efficiency.   
+ Refraktion i den mod læseretning retning.  
- Refraktion som ender i alle andre retninger.  
- Transmission.  
- Refleksion.

Jeg ved ikke om afstanden i krystal strukturen er forskellige for forskellige krystaller. Hvis ikke så betyder det, at med lavere refraktions indekser, så skal indfaldsvinklen være tættere på 0°



Så der er et lineært forhold mellem indfalds-  
vinklen og det refraktionsindex krystallen har.   
Så konklusionen må være, at jo lavere refraktionsindekset   
er, jo mindre skal indfaldsvinklen være.

Diffraktion index mod refraktion index modulation

Refraktions indekset kan beskrives ved:   
   
 er krystallens gennemsnitlige indeks  
 er ændringen i indekset, når en lys frynse er fundet i interferensmønstret i en krystal.   
 er afstanden imellem hvert grating. For braggs lov tror jeg det kan ses som d parameteren.

Det er ∆n der er spændende at kigge på.   
Jeg spurgte chatten om det er givet, at en krystal med lavt refraktions indeks ville medføre store ∆n, men den beskrev, at det ikke var det. ”The **modulation** depends **mainly on how strongly the material responds to the recording process** (e.g., laser exposure, chemical changes, etc.).”

**Examples:**

* A material with n = 1.5 (like glass) could have a tiny modulation, say \Delta n = 10^{-4} (very small bumps).
* Another material with n = 1.4 could have a **larger** \Delta n = 10^{-2} if it’s much more sensitive to light and interference patterns.

## Krystal egenskaber

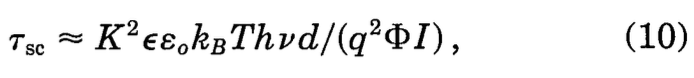
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | GaAs | LiNbO3 | LiNbO3 near- stoichiometric 48,6/51,4 |  |
| Diffraction efficiency | 1% |  |  |  |
| Response time | 0,1ms, 0,22ms ved K = 2,1um, 3,5um | ”Order of minutes” |  |  |
| Saturation intensity | “Rather low” |  |  |  |

Chatten har givet mig et overordnet indtryk af hvad der gør respons tiden. Det er et groft estimat, men den siger at

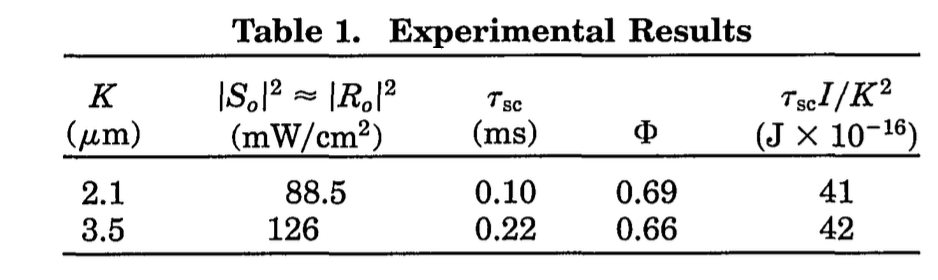
Så det kan jeg lede efter ved ukendte krystaller.

### Fra hvor?

“GaAs… Despite of the low diffraction efficiency ( usually less than 1% ) of these crystals, their fast photorefractive response time at rather low light intensity make them particularly appealing for image processing, especially for holographic-based techniques.” [3]

, “parallel to x and the spatial direction ∆” [3] [3]

exponential response time. [3]



“However, under cw illumination intensity (in watts per square centimeter), the response time for writing a holographic grating in LiNbO3 crystal is of the order of minutes” [4]

“The recording and decay curves can be approximately described by the  
 and  
   
Where is the grating buildup constant and is the dark decay time constant, estimated to be 122 and 182 ms, respectively.” [4]

Chatten siger, at det jeg skal tage ud fra det her er, at er tiden det tager at skrive til krystallen. er bare tiden, hvor informationen er gemt i krystallen. Derfor må   
 kunne repræsentere response tiden. [4]

” In this Letter we report that a near-stoichiometric crystal has been strongly reduced in vacuum to increase its response speed, and a short photorefractive response time has been observed. A nominally pure single-domain near-stoichiometric LiNbO3 crystal is grown by the Czochralski method from a congruent melt , with the addition of .”

#### Chatten svarer på relation mellem materiale of response tid.

##### 🧩 Is there a simple relationship between response time and material properties?

**Not exactly simple**, but there *are patterns*. Response time in photorefractive materials is governed by several interconnected properties. Here’s a breakdown:

##### 🔑 Response Time (𝜏) depends mainly on:

1. **Charge carrier mobility (μ)**

→ Higher mobility = faster redistribution of charges = shorter response time

(GaAs has high mobility, hence fast response)

1. **Trap density and depth**

→ Shallow traps = quicker release of carriers = faster response

→ Deeper traps = longer retention = slower response

(LiNbO₃ typically has deep traps, but near-stoichiometric versions improve this)

1. **Photoconductivity (σ)**

→ Higher photoconductivity = faster charge migration = shorter response time

(Often wavelength and intensity dependent)

1. **Light intensity (I)**

→ Response time ∝ 1/I

(So increasing writing beam power speeds up response)

1. **Applied electric field (E)**

→ Enhances carrier drift → speeds up grating formation

##### ⏱ Rough Relationship (simplified):

This isn’t exact for all materials but gives an idea: better charge transport and higher writing intensity = shorter response time.

### 🧪 So, where can you actually get this info?

* **Response time experiments**, like the ones you’re reading, are crucial.
* You can also look for parameters like:
  + Carrier mobility (μ)
  + Trap lifetimes
  + Refractive index changes vs time

Because direct modeling is very complex (involving nonlinear PDEs and material-specific behaviors), **your approach—reading and comparing results—is the most realistic path**.

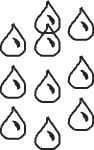
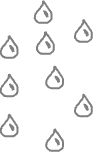
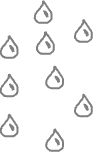
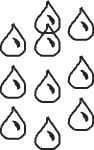
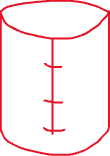
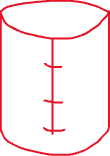
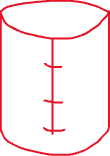
## Begreber

Spatial direction / spatial frequency.   
Hvor tæt pakket interferens mønstrene er i krystallen. Når der bliver snakket om   
spatial frequency, så er det så hvor frekvent interferens mønstrene er indenfor   
mm størrelser.



### Stoichiometric

Den ideele kemiske blanding. For LiNbO3 snakker vi om den som idéel,   
så snakker vi om lige meget Li som der er Nb. Reelt er det måske en 60/40  
fordeling.



## References

[1] Matching for realizing high-speed reading in holographic data storage system ( 2024 ), Jing Xu, Yongkun Lin, Linli Zhong, Yuping Ke, Chen He, Sheng Lin, Dakui Lin, Xiao Lin and Xiaodi Tan,   
<https://opg.optica.org/oe/fulltext.cfm?uri=oe-32-26-46259&id=565113>

[2] *Similar tests made previously:* A precision tester for studies of holographic optical storage materials and recording physics ( 1996 ), M.-P. Bernal, H. Coufal, R. K. Grygier, J. A. Hoffnagle, C. M. Jefferson, R. M. Macfarlane, R. M. Shelby, G. T. Sincerbox, P. Wimmer, and G. Wittmann  
<https://opg.optica.org/ao/abstract.cfm?uri=ao-35-14-2360&origin=search>

[3] Shaoping Bian\* and Jaime Frejlich, Photorefractive response time measurement in GaAs crystals by phase modulation in two-wave mixing, 1994  
<https://opg.optica.org/directpdfaccess/d4823231-e624-4a7b-a338790875ac1e71_12642/ol-19-21-1702.pdf?da=1&id=12642&seq=0&mobile=no>

[4] Xiao-Jun Chen, Deng-Song Zhu, Bing Li, Tao Ling, and Zhong-Kang Wu, Fast photorefractive response in strongly reduced near-stoichiometric LiNbO3 crystals, 2000  
<https://opg.optica.org/view_article.cfm?pdfKey=6cc200ab-1783-4fee-bbce59fd6dd2e3a9_64657&archive=y>

[5] Xiao-Jun Chen, Deng-Song Zhu, Bing Li, Tao Ling, and Zhong-Kang Wu, Fast photorefractive response in strongly reduced near-stoichiometric LiNbO3 crystals  
<https://opg.optica.org/directpdfaccess/6cc200ab-1783-4fee-bbce59fd6dd2e3a9_64657/ol-26-13-998.pdf?da=1&id=64657&seq=0&mobile=no>

## Referat af chatten:

### 📄 Summary from a Design Study Perspective

**Title:** *Matching for Realizing High-Speed Reading in Holographic Data Storage System***Authors:** Jing Xu, Yongkun Lin, Linli Zhong, Yuping Ke, Chen He, Sheng Lin, Dakui Lin, Xiao Lin, and Xiaodi Tan   
**Published in:** Optics Express, Volume 32, Issue 26, Pages 46259–46272 (2024)   
**DOI:** 10.1364/OE.540965

### 🔍 Design Challenge

The study addresses the challenge of achieving high-speed data reading in holographic data storage systems. The key focus is on ensuring frame rate matching among critical components: the Digital Micromirror Device (DMD), Acousto-Optic Modulator (AOM), high-speed camera, and the electric displacement table. Mismatches in frame rates among these devices can lead to inefficiencies and increased bit error rates during data retrieval.

### ⚙️ Experimental Setup

The researchers constructed a holographic data storage system incorporating the following components:

* **Laser Source:** Provides the coherent light necessary for holography.
* **Acousto-Optic Modulator (AOM):** Modulates the intensity and frequency of the laser beam.
* **Digital Micromirror Device (DMD):** Spatially modulates the light to encode data.
* **High-Speed Camera:** Captures the reconstructed holographic images during data reading.
* **Electric Displacement Table:** Holds and precisely moves the storage medium (e.g., photorefractive crystal) for data recording and retrieval.

The system’s performance was evaluated by adjusting parameters such as the exposure time and resolution of the camera, and the phase difference between the AOM and DMD.

### 📈 Key Findings

* **Frame Rate Matching:** By finely tuning the system parameters, a maximum matching frame rate of 18 kHz was achieved among the DMD, high-speed camera, and AOM.
* **Data Reading Performance:** Under conditions where the electric displacement table speed is 40 mm/s and the incident light intensity is 0.6 mW, the system attained a reading frame rate of up to 8 kHz, resulting in a data transfer rate of 5.8 GB/s.
* **Bit Error Rate (BER):** The system achieved a BER of 5%, which could be further reduced to less than 1.5% by increasing the reading light intensity.

### 🧪 Implications for Design Studies

For a design study focusing on holographic data storage systems, this research highlights several critical considerations:

* **Component Synchronization:** Ensuring precise frame rate matching among system components is vital for high-speed data retrieval and low error rates.
* **Material Selection:** The choice of storage medium (e.g., photorefractive crystals) impacts the system’s ability to handle high-speed reading and writing.
* **System Optimization:** Adjusting parameters such as exposure time, resolution, and phase differences can significantly enhance performance.
* **Future Enhancements:** Incorporating advanced image processing techniques, such as deep learning, may further reduce BER and improve data retrieval accuracy.

### 🔗 Reference

Xu, J., Lin, Y., Zhong, L., Ke, Y., He, C., Lin, S., Lin, D., Lin, X., & Tan, X. (2024). Matching for realizing high-speed reading in holographic data storage system. *Optics Express*, 32(26), 46259–46272. https://doi.org/10.1364/OE.540965

If you need further assistance or have specific questions about the study, feel free to ask!

## Chattens forslag til hvordan jeg skal blive klogere

Great observations — you’re really on the right track by asking how *materials* contribute to the *performance bottlenecks*. Let’s unpack this step-by-step from the design study perspective you’re working from:

### 🔬 How are photorefractive crystals used in the article?

In the article, the **crystals** serve as the **storage medium** — they are where the holographic interference patterns are written and later read. The crystal is mounted on the **electric displacement table**, which moves it during data writing and reading. It’s here that the actual **data density, fidelity, and speed potential** are physically realized.

So in this context:

* The **crystal is passive** in terms of logic or signal, but **active in determining how fast and accurately you can read/write data**.
* Their **refractive index modulation properties** and **response times** are key to how well they perform.

### 📉 Is the crystal the bottleneck in this system?

From what this article emphasizes — no, **not directly**. The authors focus heavily on the **synchronization** of the system’s **optical and mechanical components**: DMD, AOM, high-speed camera, etc.

However, that doesn’t mean the crystal isn’t a limiting factor in *other* ways:

* If the **crystal can’t respond fast enough**, you may not fully take advantage of high-speed optics.
* If its **modulation depth** is too shallow or **fatigue** sets in quickly, you’ll face **data loss** or need more power (affecting energy efficiency).
* If the **diffraction efficiency** is too low, reading becomes error-prone and slow.

So even if the current bottleneck is mostly the **frame rate coordination**, the **material’s physical and optical response** can become the **next limit** once that is optimized.

### 🧪 How can you gain more knowledge about what makes a “fast” crystal?

Here’s how you can dive in:

1. **Literature Search Terms:**
   * *Photorefractive response time*
   * *Diffraction efficiency of photorefractive crystals*
   * *Materials for holographic data storage*
   * *Crystal fatigue in optical storage*
   * *Carrier mobility in photorefractive materials*
2. **Important Properties to Look Into:**
   * **Photorefractive sensitivity** (how strongly the crystal reacts to light)
   * **Response time** (how fast refractive index changes can occur)
   * **Refractive index modulation range**
   * **Recording wavelength compatibility**
   * **Thermal stability and fatigue resistance**
   * **Transparency window**
3. **Common Crystals Studied:**
   * **LiNbO₃ (Lithium Niobate)**
   * **Barium Titanate (BaTiO₃)**
   * **Strontium Barium Niobate (SBN)**
   * **Bismuth Silicon Oxide (BSO)**
4. **Hands-on Tools:**
   * Use simulation software like **Emode Photonics** to simulate wave propagation and diffraction behavior in different materials.
   * Use **material property databases** (like MatWeb or literature from SPIE, OSA) to compare photonic crystal parameters.

### ✅ Summary

* In your study, the **crystal is the physical medium for storing holograms**.
* This paper focused more on **device synchronization** than crystal limitations — but the material still **matters a lot**, especially in the next step of optimization.
* You can gain deeper knowledge by looking into **response speed**, **refractive modulation**, and **diffraction efficiency** — those are often what make a crystal “fast”.

If you want, I can help sketch a mini-research plan for comparing crystals or draft some search queries to kickstart your literature review.

## Chatten giver retning til hvor jeg skal søge efter viden

### 🔑 Main Crystal Properties to Consider

#### 1. Photorefractive Effect Strength

* **Why:** Determines how well the crystal can store holograms via light-induced refractive index changes.
* **How to find it:** Look for the **photorefractive coefficient** or **change in refractive index (Δn)**.

#### 2. Response Time



* **Why:** For high-speed reading/writing, the crystal must react and reset quickly.
* **How to find it:** Often listed as **rise time / decay time**, measured in milliseconds or microseconds.

#### 3. Diffraction Efficiency

* **Why:** Indicates how effectively a stored hologram can be reconstructed (important for signal clarity).
* **How to find it:** Usually given in % or as a function of recording conditions.

#### 4. Saturation Intensity



* **Why:** Lower values mean less power needed to write/read holograms — useful for energy efficiency.
* **How to find it:** Often in units like W/cm² or mW/cm².

#### 5. Wavelength Sensitivity

* **Why:** Must match laser source used in the setup (e.g., 532 nm or 1064 nm).
* **How to find it:** Listed in crystal datasheets or literature.

#### 6. Optical Damage Threshold

* **Why:** Crystals must withstand high-intensity laser pulses during rapid reading/writing.
* **How to find it:** Often in GW/cm² — more critical for writing than reading.



#### 7. Material Transparency Range

* **Why:** Ensures light can travel through the crystal without absorption.
* **How to find it:** Given as a wavelength range (e.g., 400–2500 nm).

### 🧪 Properties You Can Likely Get Information About:

You can typically find the following from:

* Manufacturer datasheets
* Research articles
* Materials databases

Et billede, der indeholder tekst, skærmbillede, Font/skrifttype, software

Automatisk genereret beskrivelse

## Chatten giver sammenligning af krystaller:

Et billede, der indeholder tekst, skærmbillede, Font/skrifttype, nummer/tal

Automatisk genereret beskrivelse

### 🔍 Insights for High-Speed Holographic Data Storage

* **GaAs**: Exhibits the fastest response times, making it ideal for applications requiring rapid data read/write cycles. Its high photorefractive sensitivity further enhances performance in dynamic environments.
* **LiNbO₃**: Offers a balance between response time and stability. Near-stoichiometric compositions improve photorefractive properties, making it suitable for applications where moderate speed and high stability are required.
* **BSO and BGO**: While they have slower response times compared to GaAs, their high photorefractive sensitivity and low dark conductivity make them excellent for applications where long-term data retention and stability are prioritized over speed.

### 🧪 Considerations for Material Selection

When choosing a photorefractive crystal for high-speed holographic data storage, consider the following:

* **Response Time**: Critical for applications requiring rapid data access. GaAs leads in this category.
* **Photorefractive Sensitivity**: Determines the efficiency of hologram recording. BSO and BGO excel here.
* **Thermal and Photostability**: Important for long-term reliability. LiNbO₃ offers high stability.
* **Transparency Range**: Ensure compatibility with the operating wavelength of your system.

If you need further details on specific properties or assistance in selecting the right crystal for your application, feel free to ask

## Chatten om parameter til simulationsmuligheder

### 🔹 1. Diffraction efficiency

* Depends strongly on the refractive index modulation Δn.
* Higher Δn → Higher efficiency in forming a strong hologram → Faster and more robust data writing/reading.
* You can simulate how efficiently the grating stores information at different Δn values.

**Related to your design:**

→ Higher diffraction efficiency = potentially faster and more reliable readout = better for high-speed storage.

### 🔹 2. Grating spacing and Bragg selectivity

* The index affects how sharply a specific angle or wavelength is selected (Bragg condition).
* Affects how well you can multiplex many different data pages without crosstalk.
* Tighter control (high n, fine gratings) = more pages = higher data density.

### 🔹 3. Photorefractive gain coefficient (Γ)

* Depends on Δn and other material parameters.
* Essentially tells you how strong the internal electric fields and space-charge fields are for a given writing beam.
* Higher Γ = better holographic recording.

### 🧠 Quick idea:

If you want something **very practical to simulate and compare**, I’d suggest:

Simulate **diffraction efficiency vs. refractive index modulation Δn** across different crystal candidates.

It ties *directly* into how much light is diffracted (= strength of holographic recording), *and* it’s a parameter you can influence experimentally by doping, stoichiometry changes, or different materials.

**Simple relationship:**

For thin gratings (first approximation),

(meaning diffraction efficiency increases with the square of the refractive index modulation.)

## Chatten om forholdet mellem refraktions index modulation og diffraction efficiency

Mig:   
But diffraktion efficiency depends not only on what light has been refracted but also what percentage of light is being refracted in the right direction. How does that come into play in these equations?

🔵 **First:** Yes, **diffraction efficiency** depends on **two things**:

1. **How much light gets refracted** (depends on how strong the index modulation \Delta n is).
2. **How much of that refracted light goes into the desired direction** (depends on how “perfect” the grating structure is — its *periodicity* and *matching* to the light’s wavelength).

🔵 **How these two show up:** When we say “**diffraction efficiency is proportional to** ,” we’re **assuming** the grating is:

* **Perfectly periodic** (perfectly regular “bumps”)
* **Matched** to the wavelength (so that Bragg condition is satisfied)

In this perfect case, almost all the refracted light **constructively interferes** into **one strong direction** (like a laser spot), and very little leaks into other directions.

➡️ **Thus, the modulation strength** ∆n **alone decides the efficiency**.

🔵 **When imperfections matter:**

If the grating is **messy**, **random**, or **not properly matched** to the light:

* Some refracted light **scatters into wrong directions**.
* Then, the actual diffraction efficiency is **less than** what predicts.
* In that case, you need more detailed models (including things like *coupling coefficients*, *angular detuning*, etc.).

🔵 **Summary:**

✅ If the grating is perfect and the wavelength matches → diffraction efficiency ∝ .

✅ If the grating is messy or mismatched → the efficiency drops, and you can’t just trust alone.

**Tiny visual idea:**

Imagine you’re shouting in a tunnel (perfect grating) — the sound (light) focuses straight.

If the tunnel is twisted and broken (bad grating), your voice scatters everywhere.