Bacteriorhodopsin as an Analog Holographic Memory for Joint Fourier Implementation of CNN Computers

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Sz. Tőkés, L. Orzó, Gy. Váró, and T.Roska

Analogical and Neural
Computing Research Laboratory, Computer and Automation Institute,
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Abstract:

Bacteriorhodopsin has been proved to be an outstanding candidate for reversible, transient, real-time, holographic material. In this report we outline its basic physical and chemical properties, concentrating on its possible application in optical CNN implementations and in programmable opto-electronic analogic CNN computers (POAC). Different comprehensible architectures and the technical details of its applicability are also discussed.

Introduction

In this report we try to summarize the known physical and chemical properties of Bacteriorhodopsin (BR) [1] and some different modified BR forms [2], [3], [4], [5] from the point of view of its possible utilization as a transient holographic recording material, especially as a part of the POAC system [6].

Our goal is to define the possible architectures for efficient application of this material within this framework. Based on the known properties of different modified and molecular-engineered forms of BR we can estimate its potential speed and capacity within a POAC device using it as a dynamic holographic material. Feasibility of the different possible architectures is discussed. First we describe the basic properties of BR. Later we describe the fundamental structure of the POAC system within we intend to use BR as a rewritable holographic memory. Here we describe also how the CNN [7], [8] [9], [10], can be implemented optically. At last we describe some possible architectures and some results of the preliminary measurements, which tries to define the applicability of BR and its modified forms.

Bacteriorhodopsin

History & Biological primers

BR is a stable transmembrane protein of an archea bacterium, Halobacterium (Halobacterium Halobium). This bacterium lives in salt marshes. Halobacterium can survive even in bizarre environmental conditions. It prefers extremely high sodium chloride concentrations.

BR, itself, is a photon-driven proton pump. Halobacteriums use this protein to utilize the energy of light, when dissolved oxygen concentration drop below the levels sufficient to sustain respirative oxidative phosphorylation. After the absorption of a photon BR pumps one proton out of the cell through the cell membrane. Arising proton gradient provides energy for the cell. This type of energy is later transformed to chemical energy form - ATP molecules - by the application of ATP synthase enzymes.

Physical and Chemical properties

BR molecules consist of seven α-helical sub-domains. These parts of the protein form a hole, which is occupied by a co-factor, the retinal molecule. The structure of the BR molecule is depicted on the next figure (Figure 1). BR molecules aggregate uni-axially oriented, hexagonal, trimer structure. This hexagonal, crystal-like structure assembles into large clustered patches on the membrane.

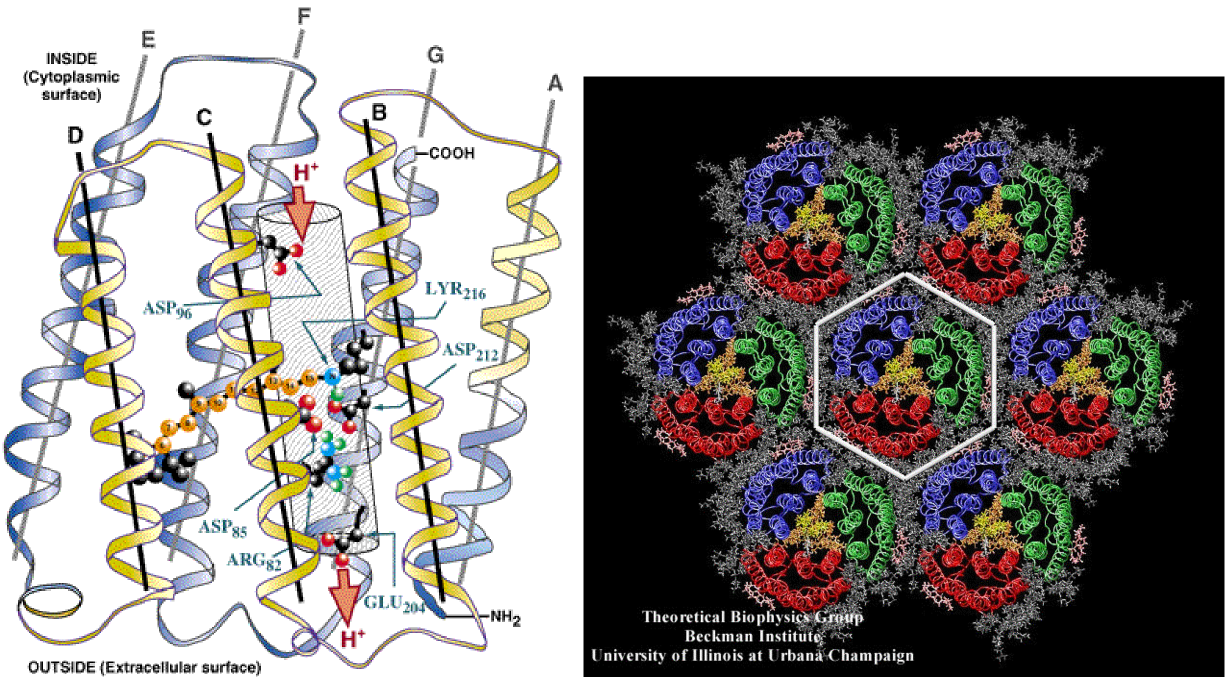

Figure 1. Structure of the BR molecule. An image about its trimer, crystal-like structure is also should be appreciated.

Photocycle

After the absorption of a photon BR goes through a sequence of chemical and physical changes [1], [11], [12]. It is including the retinal molecule's all-trans – 13-cis transformation, shifts of charges within the protein, movement of protons, that is protonation, deprotonation, and several conformational changes as well. The above characteristic changes are reflected (and manifested primarily) in the changes of the BR's absorption spectrum. Different states have different lifetimes and characteristic absorption spectra. After the photon absorption and proton transfer BR sooner or later recovers to its initial conformation. The whole sequence of transitions is called the photocycle of the BR. The quantum yield of the photocycle is relatively high (0.67). The above mentioned characteristic changes in the absorption spectra can be used for analog memory storage. The main steps of the BR photocycle are depicted on the next figure. The characteristic life times of the different states is described in the succeeding table:

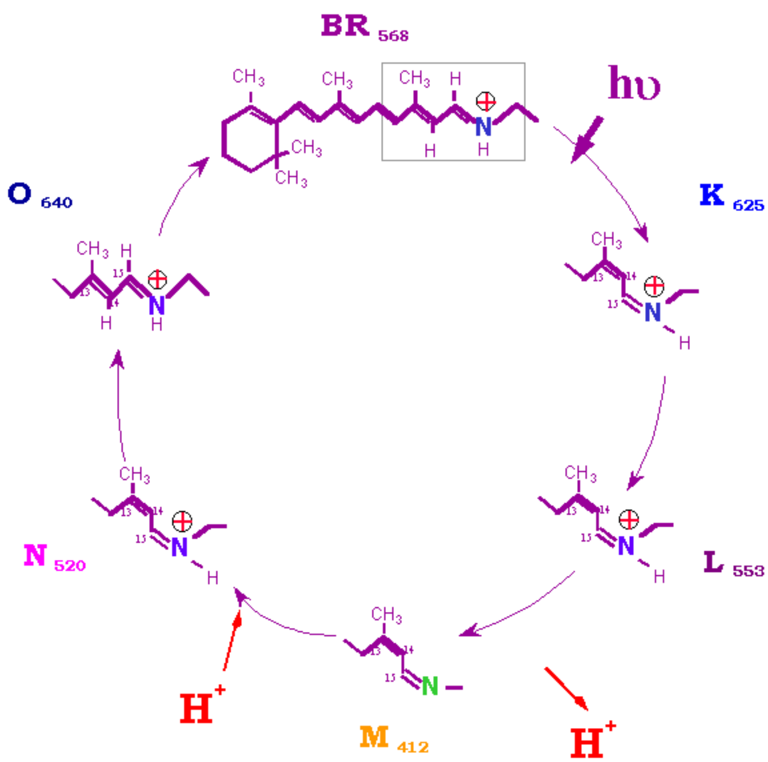

Figure 2. Photocycle of BR.

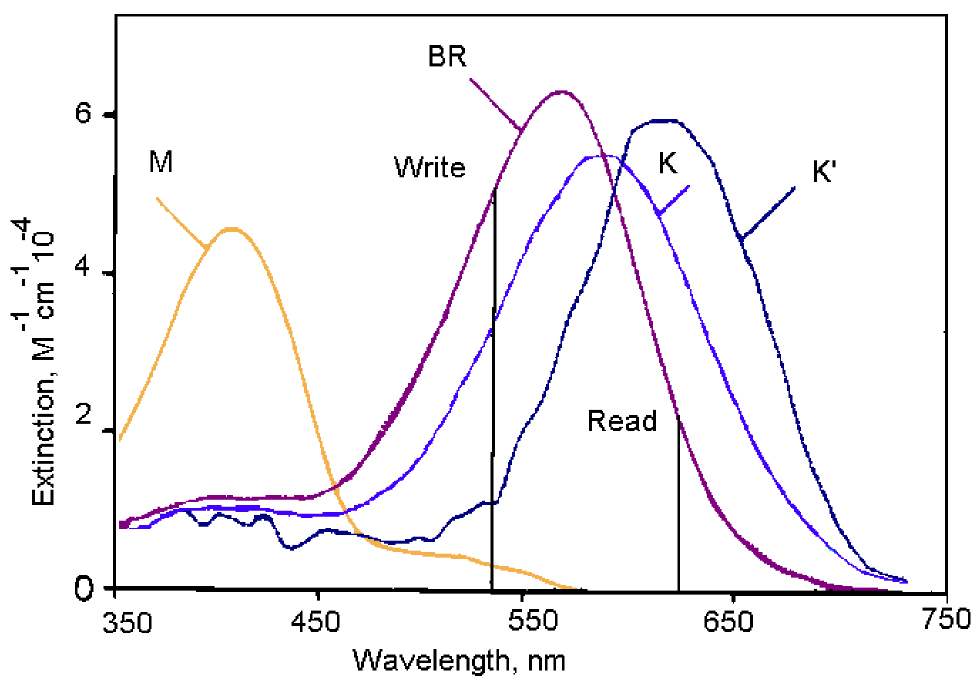

Figure 3. Absorption spectra of the different states of the photocycle.

500fs	10ps	2μs	40 μs	7ms		4ms	

$BR_{570} \rightarrow J_{625} \rightarrow K_{600} \leftrightarrow L_{550} \leftrightarrow M_{412} \leftrightarrow N_{520} \leftrightarrow O_{640} \leftrightarrow BR_{570}$

Table 1. Characteristic times of different states of the BR photocycle.

Being aware of the BR's structure and its detailed molecular dynamics, even molecular engineered alteration of it is possible. Different biologically, chemically and physically modified BR forms are available [13], [14], [15]. Several different types of utilization of BR have been suggested. An overview of these applications can be found in the paper of Birge [16], [17], [18], [19], [15], [20], [21], [23]. (These includes random access thin film memories, neural-type logic gates, photon counters and photovoltaic converters, reversible holographic media, artificial retinas picosecond photodetectors, spatial light modulators, associative memories, two-photon volumetric memories, holographic correlators, nonlinear optical filters, dynamic time-average interferometers, optical limiters, pattern recognition systems, multilevel logic gates, optical computing, and branched-photocycle volumetric memories.) In this paper the BR's applicability as a transient holographic recording material is examined particularly.

BR as a transient holographic material

Speed & resolution

It is frequently claimed [Osterhelt, Vsevolodov] that the BR has extremely high spatial resolution: higher than 5000 lines/mm. This resolution even exceeds the commonly applied optical system's capabilities. This high spatial resolution assures the feasibility of dual axis JTC implementation (see later). Sensitivity of the material is relatively low (1-80 mJ/cm^2), but it is not considerable worse than those holographic materials, which have comparable resolution and it does not require further evaluation. The writing speed of BR can be remarkably high, but of course, it depends on what kinds of states of the photocycle are used. Usually the BR's initial state (bR) and another, relatively stable intermedier (M) state are used. The bR to M transformation takes about 40μsec. This speed seems to be satisfactory for our transient holographic recording purposes, but using other states and different modified forms of BR even much higher speed can be achieved [25], [26], [27] (e.g. bR-K transition takes only about 500 fsec)(see later). One of the main problems with the utilization of BR as a temporary holographic material, is the relatively long recovery time of the photocycle (M to bR can take several hundreds of milliseconds and even second if we use different kinds of modified BR samples). If we use fresh material after all write-read cycle we can solve this problem. It can be accomplished by the appropriate replacement, shift of the recording material. There is another, more convenient way to overcome this restriction, using intense blue light that drives back the BR's M state to bR state within 50-100μsec [28]. Non-coherent intense blue light is relatively easy to produce.

So BR seems to be an adequate dynamic holographic recording medium [29], even at a very high speed. BR can be read and write more than one million times without considerable degradation. It is stable for months and persists in harsh environmental conditions. It is resistant for heat and irradiation. It is protected against oxygen and stable in a really wide range of pH (from pH1 to pH10).

Programmable Opto-electronic Analogic CNN Computers (POAC)

New optical computer architecture is arisen. Programmable Opto-electronic Analogic CNN Computers (POAC) combines programmability and optical computing, embedding CNN Universal Chips and optical holographic memories. This includes the integration of an optical processing system, usually an optical correlator, with the fast spatio-temporal processing capabilities of a CNN-UM chip for target detection. The most promising CNN-UM implementation is the latest version of the (Seville, 1998) chip. It has a 64x64 CNN [30] array. This approach seems to be useful from two points of view: It can combine the CNN-UM basically local processing – non-local, even wave based processing is solved by local feedback operations – with the optical system basically global operations. Otherwise, the CNN paradigm can provide a simple algorithmic framework, which can be used also efficiently in programming of the optical processors.

The demand for fast identification and tracking of targets e.g. in surveillance systems has been increased dramatically during the last few years [31], [32]. In several other image-processing tasks the quick recognition of particular structures is also important.

The very fast, online pre- and post-processing of the flow of image data is inescapable. Optical information processing systems can provide appropriate speed to solve these demands. However, the so far published optical processing system architectures do not seem to be flexible enough to be applicable in different computational tasks.

In recent years, several studies have demonstrated that a cellular neural/nonlinear network (CNN) type architecture, provides exhaustive programming frame for several complex, image-processing tasks [33], [34]. While several emulated digital and mixed-signal analog implementations are emerging, there have been only a few attempts to build optical or opto-electronic implementation [35]-[43] of the CNN-UM. Optical correlators, however, can implement one of the basic operations of CNN computation: the convolution.

Optical correlators

The joint transform correlator (JTC) [44], [45] is a powerful optical information-processing unit for pattern identification. It shows increased robustness comparing to a matched filter VanderLugt correlator (VLC). [46]

Advantages of JTC realization [47]-[54]:

- *Use of a spatial-domain (impulse response) filtering (no previous calculations and computer processing is needed to synthesize the Fourier–domain filters which are necessary for VLC).*
- *The JTC has a higher space-bandwidth product and a lower carrier frequency.*
- *It has a higher index modulation.*
- *It is suitable for real time applications.*
- *It is much more robust against vibrations and misalignment compared with the VLC and its robustness is comparable with that of the incoherent correlators.*

Drawbacks of JTC:

- *It suffers from moderate (lower) detection efficiency when applied to multiple target recognition or targets embedded in intense background noise.*
- *Furthermore, high spatial coherence is required, but it does not need large coherence length.*

- *The JTC method is less efficient from energetic point of view as the first order diffractive beam, which is providing the desired convolution, carries only about 1/8th of the incident energy.*

However, these drawbacks can be alleviated by applying recently developed methods (phase encoding - both in the spatial and Fourier domain -, zero-order elimination, incoherent hologram superposition and read-out)

The following equations (1,2,3) describe mathematically the operations of JTC.

$$Input = s(x+x_0,y)+t(x-x_0,y) \tag{1}$$

Where s and t corresponds to the input image and to the template.

$$\begin{aligned} &Joint\ Power\ Spectrum = S^2(\alpha,\beta)+T^2(\alpha,\beta)+ \\ &+S(\alpha,\beta)e^{-i\varphi_s(\alpha,\beta)}T(\alpha,\beta)e^{i\varphi_t(\alpha,\beta)}e^{-i2x_0\alpha}+ \\ &+S(\alpha,\beta)e^{i\varphi_s(\alpha,\beta)}T(\alpha,\beta)e^{-i\varphi_t(\alpha,\beta)}e^{i2x_0\alpha} \\ &\text{where } S(\alpha,\beta)e^{i\varphi_s(\alpha,\beta)} \text{ and } T(\alpha,\beta)e^{i\varphi_t(\alpha,\beta)} \\ &\text{corresponds to the Fourier transforms of} \\ &s(x,y) \text{ and } t(x,y). \end{aligned} \tag{2}$$

$$\begin{aligned} Output &= s(x,y)*\bar{s}(x,y)+t(x,y)*\bar{t}(x,y)+ \\ &+\bar{s}(x-2x_0,y)*t(x,y)+s(x+2x_0,y)*\bar{t}(x,y) \end{aligned} \tag{3}$$

The previous optical CNN implementations, however, had used mainly the VLC type correlator. The main problem with optical CNN VLC implementation is the slow, offline construction of the appropriate complex, computer designed holographic filter, corresponding to the necessary template. This design is sensitive for the precise positioning of the elements.

Basic structure and function of this design

In our approach, the joint Fourier transform correlator (JTC) will be used in a novel way for preprocessing, since it accomplishes the basic feedforward-only CNN operations. For example, this makes it possible to realize e.g. mathematical morphology (MM) processing in the CNN framework. The basic plan of the JTC based POAC is shown in Figure 4.

In the proposed architecture the unknown input image from an electronically addressed spatial light modulator (ESLM) [55] or optically addressable spatial light modulator (OASLM) is correlated with the template(s) considered as reference image(s).

Laser 1 is the coherent light source (red, He-Ne). Lens FL1 Fourier transforms the images on the OASLM in which the interference fringes are recorded.

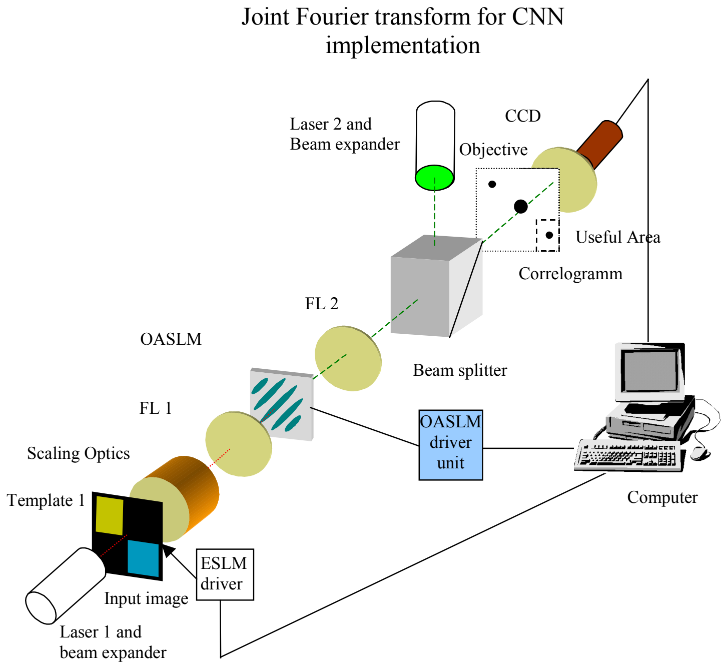

Figure 4. The experimental setup for JTC–CNN implementation measurements.

Presently, we use a moderate resolution OASLM from Jenoptik GmbH. To increase the processing capability, a higher resolution OASLM will be used. These high resolution OASLMs can be liquid crystal devices (e.g. from CoreTek Inc), PQW-SLMs (QuantaImage) or special bio-engineered materials like BR. The interferogram between the images is read-out by the light of laser 2 (green, He-Ne) and Fourier transformed by lens FL2 and projects the correlation peaks onto CCD camera. A personal computer (PC) is used to drive the image SLM.

So a classical JTC is installed with OASLM as the holographic material. Presently, both the input images and the templates are binary images. The output, the cross-correlation (convolution) terms, is recorded by a CCD camera. Next figure (Figure 5) shows the current optical correlator setup.

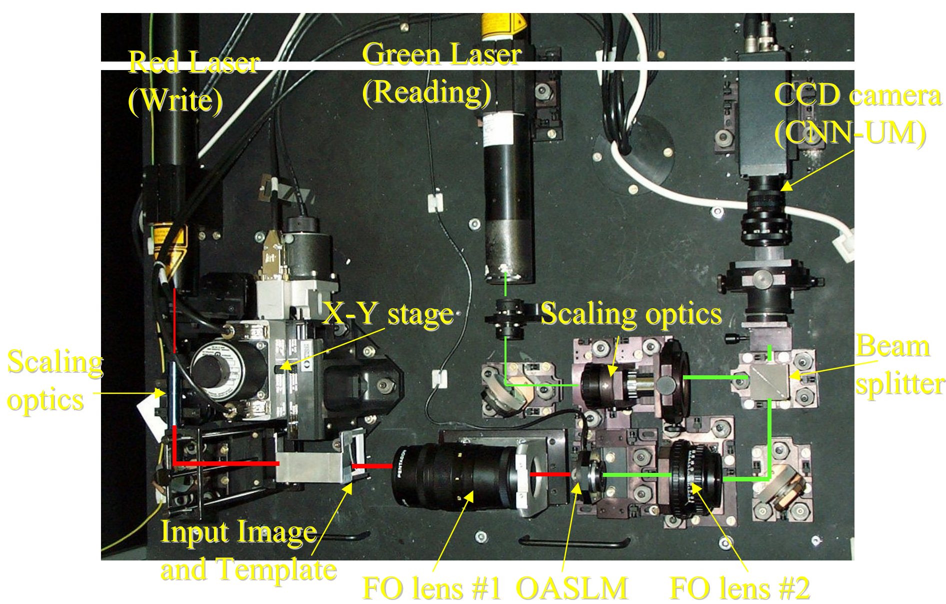

Figure 5. Current POAC JTC optical correlator setup

Improved JTC architecture

More complicated processing can be carried out by the composition of our optical CNN implementation with CNN-UM chips. The basic structure of the proposed architecture can be seen in Figure 6. Possible advantages of POAC realization:

- *The large neighborhood templates can find complex images on the input image.*
- *A VLSI implemented CNN-UM can perform the necessary further computations, considering the feedback and complex algorithms.*
- *The CNN-UM can solve the adaptive scaling and thresholding of the optical feedforward only CNN (JTC) input*

So the optical, feedforward only CNN implementation's output can be the optical input of the VLSI CNN-UM chip.

By the modification of the amplitude distribution of the reading light beam we can implement an additional template operation. The scheme of this operation is also denoted in Figure 6. This architecture provides the possibility to ensure adaptively the balance between input image and primary template's illumination. If the primary template is only a dot (Dirac delta), the reconstructed correlation image should be the same as the input. By adaptive changes of the input image's illumination we can achieve optimal reconstruction. Assurance of this balance is essential and usually unavoidable for any type of further processing. In the followings we can use an additional template (t2 in Figure 6) for programming the POAC system. In this case much higher speed computation can be achieved, which works with speed of light.

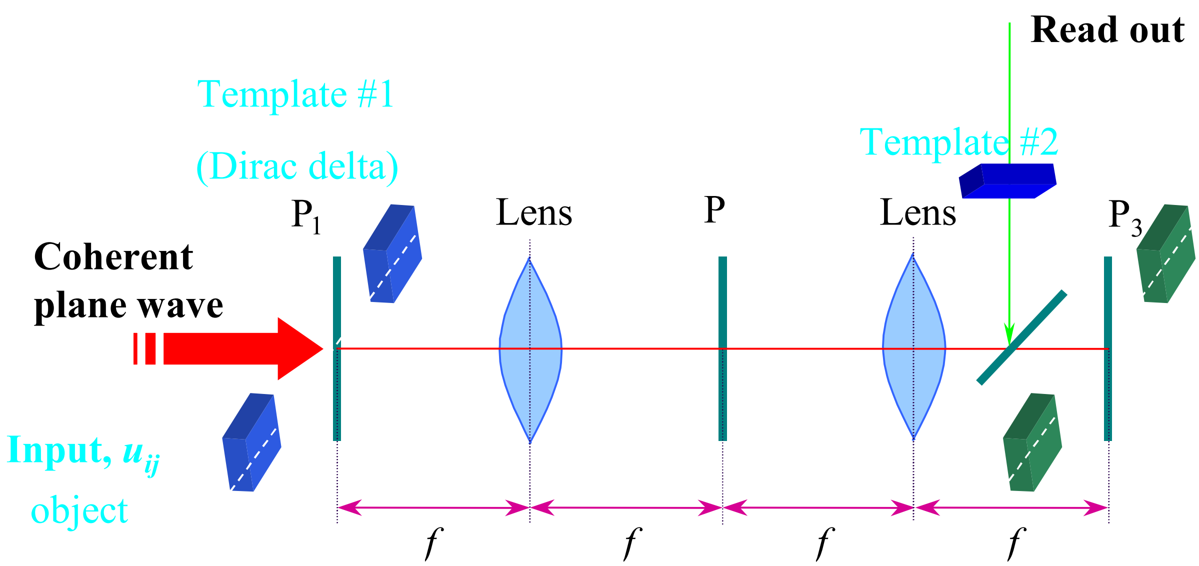

Figure 6. The proposed Programmable Opto-Electronic Analog CNN (POAC) computer architecture.

Mathematically the next equation can describe the operations.

$$
\begin{aligned}
&Output = F^{-1}((F(s(x-x_0)+F(t_1(x+x_0)))^2 F(t_2(x))) = \\
&= F^{-1}(T_2(\alpha)(F^2(\alpha)+T_1^2(\alpha)))+ \\
&+\underline{\bar{s}(x-2x_0)*t_1(x)*t_2(x)}+ \\
&+\underline{s(x+2x_0)*\bar{t}_1(x)*t_2(x)}
\end{aligned}
\tag{4}
$$

where F and F^{-1} are the Fourier transform and its inverse

Large neighborhood templates

Main advantage of the optical implementation, that there is no harsh limitation on the size of the applied templates as in the case of VLSI implementations. So by the POAC computer it is easy to implement multi-scale image processing tasks by applying a set of scaled templates.

Advantages

POAC has several advantages comparing the former approaches. It is combining high-speed analog optical and electronic processing with programmability. The CNN's nearest neighbor connectivity is extended by the optical system's much wider coupling. Within this architecture we can carry out computation in several levels of the processing, e.g. we can solve image processing tasks in the Fourier domain besides the image and correlation plane. By the CNN's optical implementation, arbitrary size of B template operation can be accomplished. Some of the processing can be executed at the speed of light. The bottleneck of the optical correlator and so the feedforward CNN optical implementation is the resolution of the OASLM. In the current setup we are using 30 line-pairs/mm resolution liquid crystal optically addressable spatial light modulator (Jen-optics). This fact presents severe limitations on the applicable optical devices (focal length and precision of the lens) and the possible size of the input images as well. Even the types of different feasible architectures are limited by this low resolution. The aimed decrease of the system size, prospective further miniaturization, also requires the application of a much higher resolution holographic material like BR.

BR in POAC

We intend to use BR as a transient holographic material within the POAC framework. Due to the BR high resolution and speed it can provides an excellent solution.

JTC

In the current setup we are using joint transform correlator for the implementation of the convolution. However, in this architecture the employable surface of the input is relatively low so the majority of the applied light power is wasted. To increase the effective area of the input we should use a dual axis JTC architecture (see Figure 7). In this case the input image and the reference image (template) can utilize the whole surface of the ESLMs. Even an OASLM can be applied at the input. Dual axis JTC require high-resolution holographic material, therefore BR seems to be adequate for this purposes.

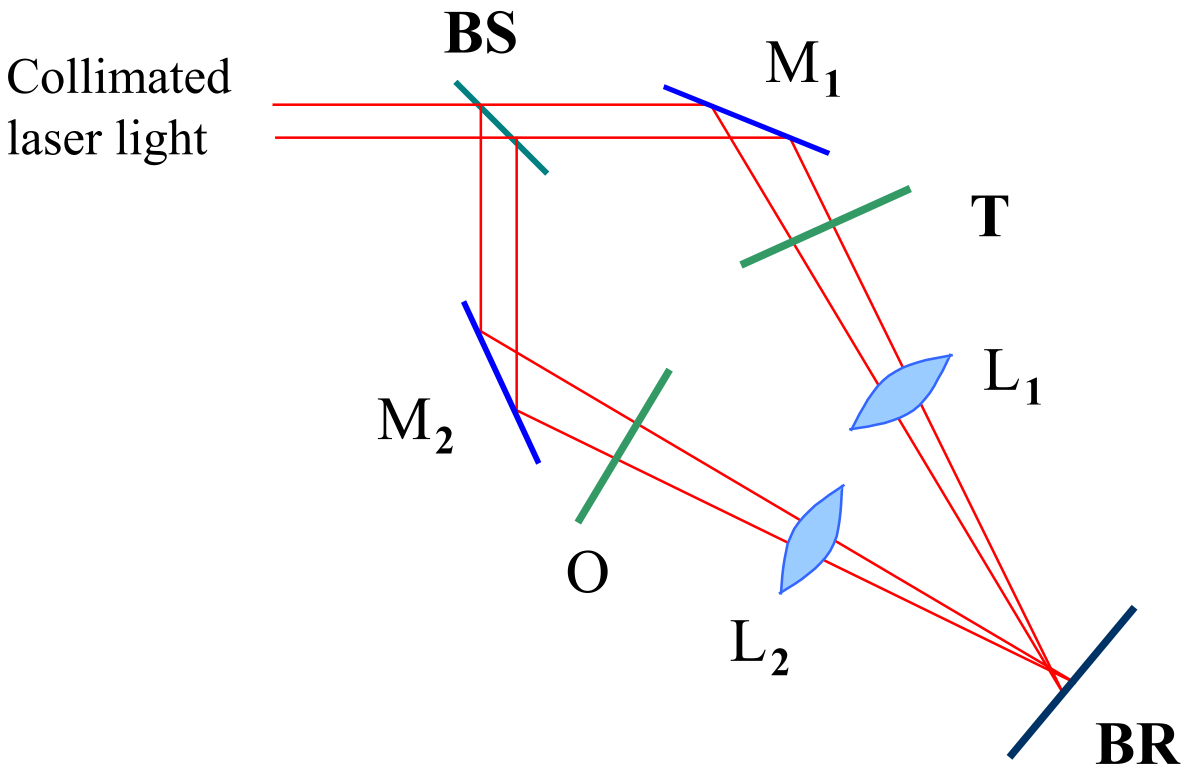

Figure 7 Dual axis architecture for holographic recording.

Possible Implementations

Due to the BR special structure, polarization holography (briefriengence) based architecture [56], [57], [58], [59], [60] seems to be fruitful for transient holographic recording. If the writing light beam is linearly polarized then only those molecules will be written whose orientation lies according to the corresponding direction. Such a way photoinduced birefringence is achieved. This way BR can be write and read with the same wavelength, but of course with different intensity and polarization. This method simplifies the architecture and considerable noise removal is achievable. Next figure (Figure 8) depicts the architecture using BR with polarization holography for the POAC implementation. The writing wavelength has to be optimized for the efficiency of writing and also for the necessary relatively big change of the refractive index. At this ‘ideal’ (635nm) wavelength, relatively chip and small diode lasers are available.

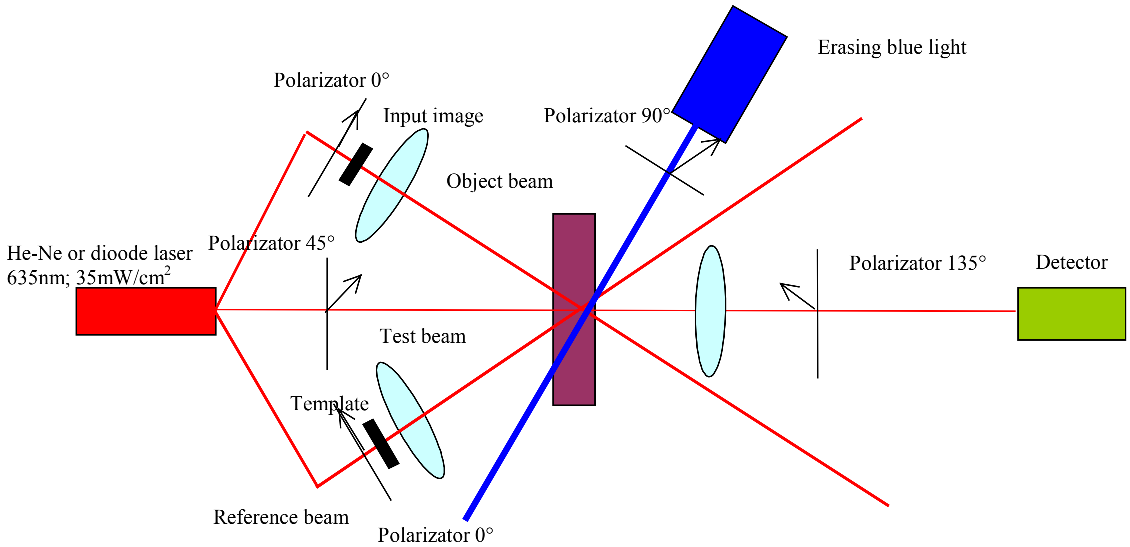

Figure 8. The bR birefringence is the strongest at the 635nm wavelength (20mW diode lasers can be achieved on this wavelength). The polarization of the object and reference beam is 45° to the perpendicularly oriented polarizator and analizator of the test beam, thus the bleached bR molecules can lead measurable modulation change. The applied blue light is polarized perpendicular to the object beams, so it can enhance the birefringence capacity of the material (drive the misleading M forms back to the BR state). Recorded holograms can be erased by a strong, blue light flashes. The cycle length can be decreased to 100µsec and so 10 kHz frame rate can be achieved. The actual architecture certainly can be different from the schematic one (writing and reading directions can be opposite etc.).

In our first experiments a more simplified BR JTC collerator architecture is suggested. In this case we use a single axis JTC setup and there would be only one Fourier optic lens in the system (Figure 9).

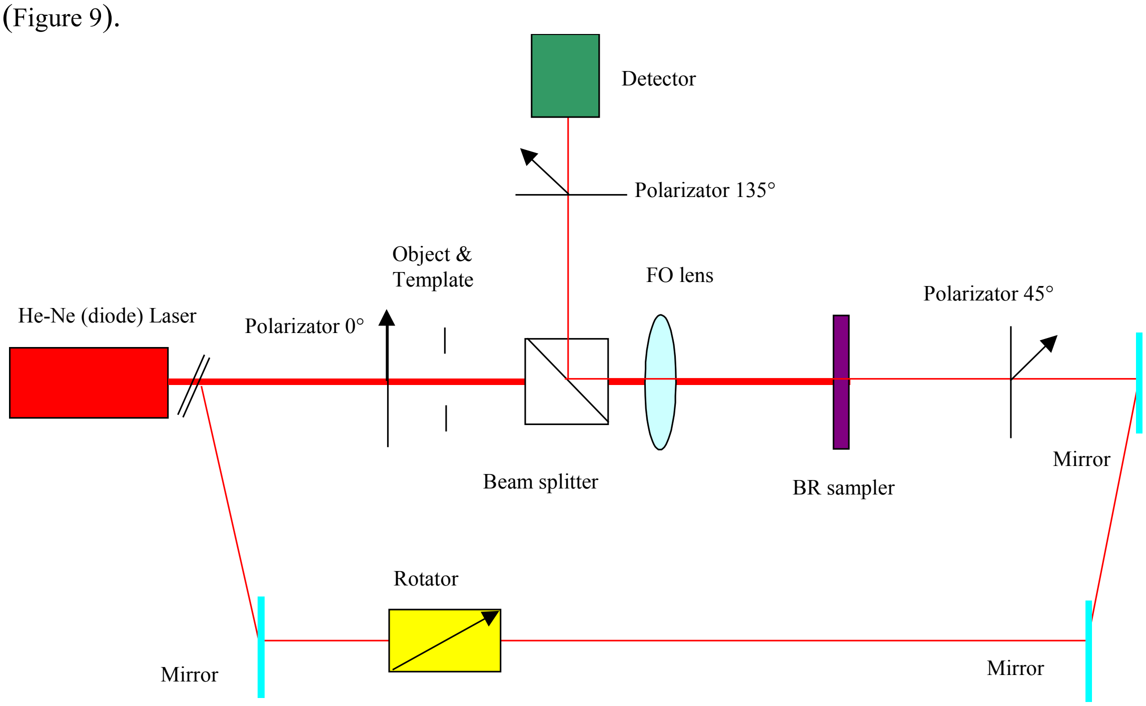

Figure 9. Simplified polarization holography based, single axis JTC BR correlator architecture.

There can be slight difference between the colors of the writing and reading lasers. In our original approach we used an architecture, where the writing (red) and reading (green) lasers were different. However the relatively thick BR films (high optical density is necessary for the desired big diffraction changes) can make this solution less feasible.
Refractive index changes can be utilized with or without the polarization holography. We can use these changes for phase modulation (same or different writing and reading wavelengths),

Other Possible Architectures

BR provides the possibility of the further speeding up of the processing. If we use other states of the photocycle even nanosecond computation time seems to be achievable. Only the device's size and the light speed delimit it.
Applying alternative architectures - (see earlier) - we can do several operations with a recorded hologram. In this case the applied detector's speed define primarily the overall performance.

Preliminary measurements

To test the applicability of BR as a holographic recording material in the POAC system, several measurements have been done.

We have examined, what is the achievable resolution with our BR samples. These samples were TEA modified, dry BR films with 20μm width, [Váró et al.].

It should be note, that the overall speed of the photocycle changes in different modified BR forms (AP, wild type, TEA, humidity, temperature etc.):
We measured the resolution of the BR samples by self-diffraction.

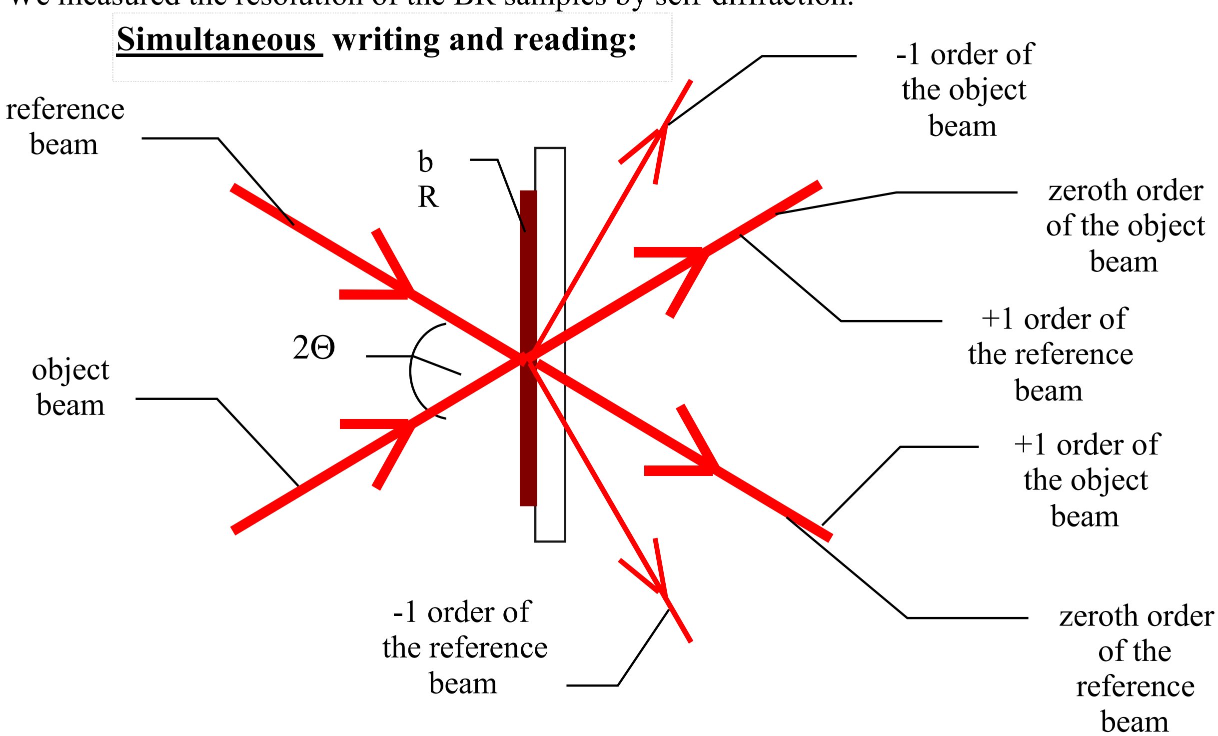

Figure 10. Self diffraction experiment

Initially the resolution appeared to be much lower (the maximal resolution was approximately 300 lines/mm (Figure 11)), than it is usually claimed in the BR literature (5000 lines/mm).

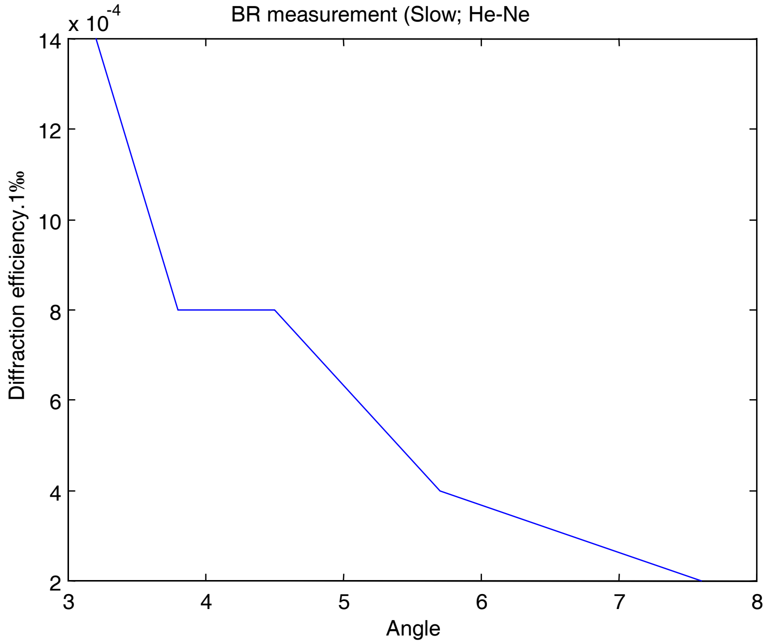

Figure 11. Self diffracted light (1^{st} order term) intensity as the function of the incident light intensity.

However, due to the fact that optical correlator architecture is to be implemented, the overall resolution is delimited by the resolutions of the lens and other optical elements (300-400 lines/mm). So even this apparently 'low' resolution can be satisfactory for our purposes.

Originally we thought that although the resolution of the BR material is really high, the vibrations of the system degrade it. We tried to minimize and decrease the vibrations of our experimental setup, as it is always important in holographic recording. We used an optical bench (optical table with inner relaxation properties) with elastic basis (tennis balls). As we are not able to separate the noise sources, we have to use the system's summed apparent resolution in our further design plans and experiments. In the correlator architecture we have to consider a strict and rigid architecture to avoid vibrations.

We could recognize remarkable dynamics in the BR sample's response. That is, after an abrupt increase (the peak efficiency can be even higher than the measured one, but the used laser power meter was relatively slow) the efficiency decreases considerably by the time within seconds. It is probably caused the bleaching of the BR. Aggregating effects of vibrations can lead similar results. However, if we decreased the writing light intensity, the BR response is much slower and the effects of bleaching decreased. Oppositely, if we increased the writing light intensity the dynamics appears to be much faster and bleaching becomes more powerful.

Another finding of our experiments was that the positive and negative first order terms are not symmetric. There can be found relatively big amplitude (positive) first order terms under the zero order terms and it is more stable than the other (negative) first order term.

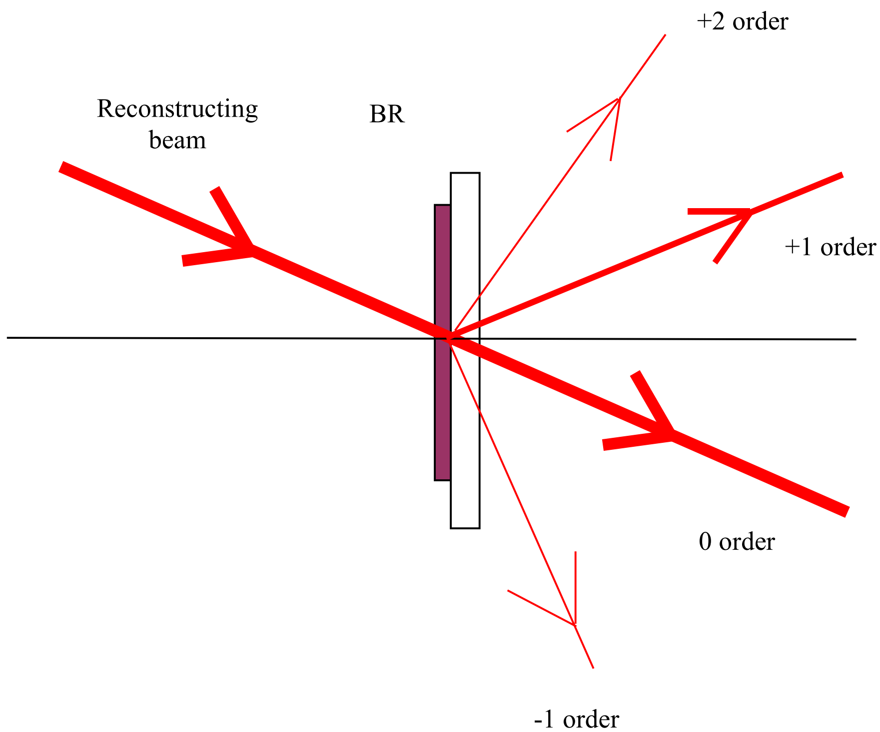

Figure 12. Asymmetry of the positive and negative terms in thick holographic recording in the BR sample.

We measured the diffraction efficiency of this term. It can be seen - Figure 13 - that although the diffraction efficiency is lower than 1‰ but still much higher than that of the (positive) first order term and it can be detected even in big incident light beam angles.

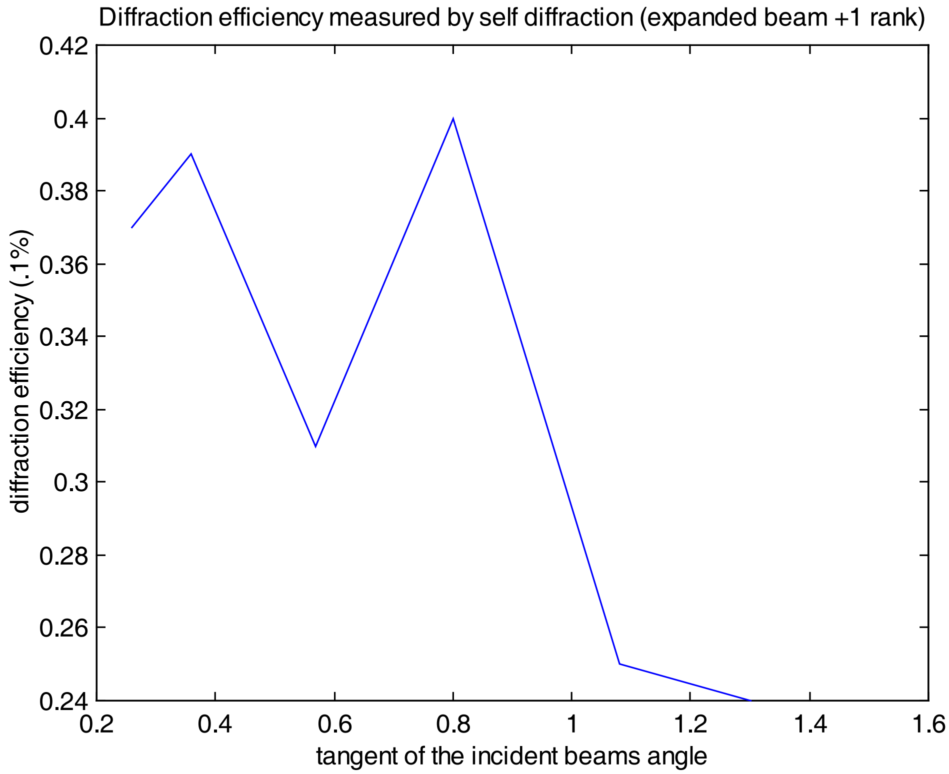

Figure 13. The positive first order term's diffraction efficiency as the function of the tangent of the incident light beam angles.

Our diffraction efficiency measurements were not too accurate – as it can be seen in the above figures - due to inherent dynamics of the material and the applied measuring method. Nevertheless it can corroborate, that the resolution of the BR is immense. More than 1000 lines/mm resolution is confirmed within our setup.

This detected asymmetry of the negative and positive first order terms is the consequence of the 'thickness' of the BR sample. As the written gratings resolution increases the sample become relatively thick and in thick holograms the only one of the first order terms are stable. Therefore, the measured low resolution was not the consequence of the vibrations but the thick holographic recording.

In the final architecture we have to consider the above outlined effects of the thick holographic recording in the BR sample as well. So it seems to be useful if the writing and reading light beams are on the same axis.

Conclusion

As it was claimed earlier[61]-[66], we were able to show been shown that BR is an excellent choice for holographic recording material in POAC system. It can provide the necessary resolution and speed. Using molecular engineered versions or modified forms of this material and alternative architectures even this (10KHz) speed can be further accelerated. Applying this material in the POAC system immense reduction of the system's size is achievable also.

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