HOLOGRAPHIC RECORDING IN BACKTERIORHODOPSIN BY SHORT LIGHT PULSES

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ABSTRACT
Optical and holographic properties of bacteriorhodopsin recording materials are considered. The use of short light pulses for recording in BR materials is shown to lead to a decrease in their sensitivity and diffraction efficiency. The relationship between BR properties and the write pulse width is shown to depend on the photosensitivity of BR short-living forms.

1. INTRODUCTION
Issues of development, study and application of bacteriorhodopsin (BR) based photocarriers have been discussed in a number of papers [1-4]. In our investigation of their photophysical properties we
earlier [3] found conditions under which a dynamical reprogrammable hologram recorded in such materials could have a practically constant value of the diffraction efficiency for unlimited time. As shown [3], pulse recording of a reprogrammable hologram within a time interval of the order of 10 ms allows for parallel switching of over 10,000 high-speed data channels with the data transfer rate being up to some gigabits per second.

However, it was found that an increase in the speed of recording resulted in a fall in the photosensitivity and diffraction efficiency. This paper presents the results of our study of effects of the recording speed upon the optical properties of BR-based photocarriers and ways to improve their sensitivity and operational speed.

2. OPTICAL PROPERTIES OF BACTERIORHODOPSIN

The main feature of the optical properties of BR is a closed photochemical cycle [4]. In the absence of light BR is in the stable form \( \text{Br} \) and have the absorption maximum in the range of 0.57 \( \mu \)m. Light of the wavelength near to \( \lambda = 0.57 \mu \)m first generates a series of fast changes in its spatial structure (forms J, K, L) and then conversion into the metastable form M having the absorption maximum in the range of \( \lambda = 0.412 \mu \)m.

In the absence of light the metastable form M relaces spontaneously into the stable form Br. Dark relaxation of the metastable form M into the stable Br passes as well with generation of a series of transient short-living forms. Total lifetime of the forms J, K, L is several tens of microseconds. Lifetime of the form M may be as long as several tens of minutes.

Practically every transient form of the cycle (J, K, L, M) is photosensitive. Their exposure results in a direct transition from a transient form to the stable form Br.

Under the conventional method [1,3,5] information is recorded in BR by exposure of its stable form Br, i.e. by use of light of the wavelength near to 0.57 \( \mu \)m. Spatial distribution of Br- and M-forms is commonly considered as the result of recording since these very forms provide for the maximum contrast, record lifetime and have the most different refractive indices.

3. EFFECT OF THE RECORDING TIME ON THE CONTRAST AND SENSITIVITY

Tests were carried out with a carrier sample comprising crown-ester-modified BR film in gelatine matrix on a glass substrate. Unmodified-BR-based carrier was used as a check sample.

The optical scheme for measurement of the carrier sensitivity and contrast as functions of the width of the write light pulse is presented in Fig.1 including an exposing YAG-laser operating on 0.53
μm, acousto-optical modulator, photocarrier sample, reading He-Cd laser operating on 0.44 μm, acousto-optical modulator and photodetector.

A low-intensity reading beam of the He-Cd laser passes through the exposed area of the carrier and is detected by the photodetector. Since the wavelength of the reading laser lies within the M-form absorption range of BR, change in absorption of the read beam characterizes the number of molecules passed from Br- to M-form.

To determine the sensitivity as a function of the write time the sample is exposed with a single short pulse. The width of the light pulse is varied while its energy is kept constant by varying the diffraction efficiency of the acousto-optical modulator. The sensitivity is defined as area-normalized energy of the exposing light beam needed for photostimulated transition of 50% BR molecules from the stable Br-form to the metastable M-form.

Fig. 2 presents normalized dependence of the sensitivity of the test and check samples as a function of the exposing light pulse width. It is seen that decrease in the exposing light pulse width results in the practically same decrease in the sensitivity of the two samples.

In order to study the carrier contrast as a function of the write time the sample is consecutively exposed by single light pulses of width τ=100 ms and τ=2 μs. Energy of the pulses increases until the carrier reaches the maximum write contrast (saturation). The contrast is defined as the maximum possible photostimulated change in optical loss in the absorption range of M-form. It is found out that the maximum write contrast of the two samples at τ=2 μs. is less by about two times than the contrast at τ=100 ms.

The obtained results allow us to make a conclusion about the mechanism of effect of the write time upon the optical properties of BR. They show that with the write pulse width comparable to the lifetime of the short-living forms (J, K, L) of the photocycle of BR the optical properties are substantially deteriorated due to transitions photostimulated by the high-power write pulse that pass without generation of the metastable M-form. This conclusion is also confirmed by the analysis of the mathematical model (1) describing the cytogenetics of BR taking account of overlapping of the photosensitivity spectra of its Br-, K-, and M-forms:

\[
\frac{dK}{dt} = \alpha I_{w}Br - \beta I_{w}K - cK \\
\frac{dM}{dt} = cK \\
Br + K + M = 1
\]

where \( K \) is a value proportional to the number of BR molecules in short-living form, \( t \) - time, \( \alpha \) - photosensitivity of the Br-form, \( I_{w} \) - intensity of the write light pulse, \( Br \) - value proportional to the number in the Br-form, \( \beta \) - photosensitivity of of the short-living form, \( c \) - coefficient of relaxation.
from short-living to metastable form, $M$ - value proportional to the number of BR molecules in the metastable form.

4. HOLOGRAPHIC PROPERTIES IN CASE RECORDING OF HOLOGRAMS ON M-FORM OF BR

The most efficient holographic record in BR is produced by spatial distribution of Br- and M-forms. As seen from the above discussion, at a high recording speed the conventional method (pulse exposure of Br-form) is low-efficient due to a dramatic decrease in photosensitivity and dynamic range of the carrier. To save high photosensitivity and diffraction efficiency (DE) of pulse-recorded holograms we recorded them in two steps. At the first step BR was converted into M-form by exposing the carrier with read light of the wavelength within the photosensitive range of the Br-form.

High-speed recording was performed at the second step by pulse exposure with light of the wavelength close to maximum of photosensitivity of the M-form.

Fig.3 presents the optical scheme for recording holograms on M-form of BR. It consisted of writing pulse laser operating at 360 nm (third harmonic of YAG-laser), modulator, light splitter, BR-based carrier, reading semiconductor laser operating at 650 nm and photodetector.

The writing laser generates light pulses. The modulator controls their power and width. The splitter splits the light beam into two beams of the same power. Passing through the mirror the two beams converge into one spot on the photodetector and interfere. The beam of the reading laser is directed to the same spot. Under effect of read light BR-carrier passes to metastable M-form and becomes photosensitive to light of the writing laser. In this way a hologram is recorded in the photocarrier.

Fig.4 shows DE of a hologram recorded in the crown-ester modified sample of BR-carrier as a function of the read light intensity at different power of the read beam. It is seen that maximum DE decreases both with increasing read light intensity (as in the case of recording on Br-form) and with its decrease below the optimal level. Comparison to the case where a hologram is recorded on Br-form with 0.63- μm light and read with 0.44- μm light (photosensitive range of M-form) also shows that the maximum DE is reached at a write light power about one-fifth as large.

4.1. Dynamic properties

In order to study dynamic properties we recorded holograms with a single light pulse of constant power and different width. It was found that in case the record is made by direct transition of the photocycle forms $M \Rightarrow Br$ (rather than multistep transition $Br \Leftrightarrow L \Rightarrow M$ as in the conventional scheme), material sensitivity does not decrease with decreasing write pulse width.
Fig. 5a presents the oscillogram of the photodetector response in case the read beam power is 0.5 mW and write pulse width is 15 µs. Fig. 5b shows the response at the read beam power 1 mW and the same parameters of the write pulse (sweep time 1 s). It is seen that DE relaxation obeys to the exponential law and its speed increases with increasing write light power as in the conventional scheme.

4.2. Stabilization of diffraction efficiency

Below are shown the results of DE stabilization by way of multiple regeneration of the hologram. Record regeneration was performed on a part of the carrier of about 1 mm in diameter with repeated series of write light pulses of $\lambda=360$ nm and width $\tau=10$ µs. Average power of the modulated read light beam of $\lambda=650$ nm was about 0.5 mW.

Figures. 6 a, b, c show the oscillograms of the diffracted signal at the period of write pulse searies $T=500$ ms (a), $T=200$ ms (b) and $T=100$ ms (c ) (sweep time -1 s). Fig.6d shows the oscillogram of the diffracted signal at the moment of the hologram regeneration at the period 100 ms (sweep time -100 µs).

It is seen that DE stabilizes in time when the period of regeneration decreases and at the period of 100 mS its variation is not more than 10%, with DE level being about 0.5%.

Due to small write pulse width $\tau$ and relatively large regeneration period $T$, it becomes possible to record and regenerate consecutively up to $N \leq T/\tau$ ( i.e.. up to 10.000 -20.000) independently reprogrammed holograms.

5. CONCLUSION

• Under pulse exposure of BR-based material within the photosensitive spectral range of Br-form (0.5-0.65 µm) its sensitivity and maximum DE decrease with decreasing exposing pulse width.

• In case material is exposed with light in the absorption range of M-form and the hologram is read with light in the absorption range of Br-form its sensitivity becomes fivefold as large and does not vary when the exposing light pulse width decreases.

• The obtained results shows possibility to get efficient control over light beams of $\lambda=0.5$-0.65 µm. Thus, it is feasible to implement an optical switch using the red-orange range semiconductor lasers as input channel light sources. Owing to shorter light pulses width and longer period of hologram regeneration the studied method for hologram recording allows the number of independently reprogrammed holograms to be up to 20000 as large.

• The obtained results confirm the prediction for a dynamically reprogrammed hologram array for switching more than 10000 optical data channels at the transfer rate of over 1 Gbit/s.
7. REFERENCES


Fig.1. Optical scheme for measurement of the carrier sensitivity and contrast as functions of the light pulse width.

Fig.2. Normalized dependence of the carrier sensitivity upon the exposing light pulse width.

Fig.3. Optical scheme for pulse recording of holograms on M-form of BR

Fig.4. Diffraction efficiency of the hologram recorded in the sample of modified BR carrier as a function of read light intensity at different power of the read beam.

Fig.5. Oscillograms of photodetector response at write pulse width 15 µs and read beam power 0.5 mW (a) and 1 mW (b). Maximum DE - 0.5%. (Sweep time - 1 s, input range - 100 mV).

Fig.6. Oscillograms of the diffracted signal at the sequence of write pulses with the period (a)-T=500 ms, (b) - T=200 ms and (c) T=100 ms (sweep time - 1 s); (d) - an oscillogram of the diffracted signal at the moment when the hologram is regenerated at T=100 ms (sweep time - 100µs).
He-Cd laser

Modulator

BR-film

Photocell

YAG-laser

Modulator

Normalized Sensitivity

TIME (μs)

Normalized Sensitivity

TIME (μs)

Original

Modified